E7.3 10689.
CR-132260

AN INVESTIGATION TO DETERMINE THE OPTIMUM MONITORING SITES FOR PLACING ERTS DATA COLLECTION PLATFORMS IN A RIVER BASIN

E73-10689) AN INVESTIGATION TO DETERMINE THE OPTIMUM MONITORING SITES FOR PLACING ERTS DATA COLLECTION PLATFORMS IN A RIVER BASIN M.S. (Alabama Univ., University.) 112 p HC $7.75 CSCL 08H G3/13 N73-26314 Unclas 00689

by

CHARLES LAMAR LARRIMORE

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil and Mineral Engineering in the Graduate School of The University of Alabama

UNIVERSITY, ALABAMA

1973

The enclosed Masters Thesis was written in connection with the project:

INVESTIGATIONS USING DATA IN ALABAMA FROM ERTS-A

Contract NAS5-21876
(Proposal No. 271)

Principal Investigator

Dr. Harold R. Henry (UN604)

Thesis Title

"An Investigation to Determine the Optimum Monitoring Sites for Planning ERTS Data Collection Platforms in a River Basin"

by

Charles Lamar Larrimore

Submitted to

Goddard Space Flight Center
National Aeronautics and Space Administration

by

Bureau of Engineering Research
The University of Alabama
University, Alabama

ACKNOWLEDGMENTS

The author is indebted to Dr. George P. Whittle for his interest, valuable suggestions, and constructive criticisms which contributed to the completion of this investigation.

Thanks are due Dr. Edmond T. Miller and Dr. Harold R. Henry for their suggestions toward improvement and completion of this study.

Gratitude is also extended to Mrs. Betty Mills for her expert typing of the final manuscript.

A very special word of thanks is given to the author's parents, Mr. and Mrs. Dennis L. Larrimore, for their continued encouragement and support throughout the author's entire college career.

Acknowledgment is given to the Environmental Protection Agency for financial support provided through a traineeship, EPA-T900-340, Dr. George P. Whittle, Director.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 General

A new and comprehensive view of Earth is needed to cope with environmental problems, as well as with difficulties caused by an expanding population and the depletion of natural resources. Earth must be viewed in its entirety as problems with the air-ocean-land system are global in extent. Earth-orbiting satellites, including the Earth Resources Technology Satellite (ERTS), have been developed which are able to remotely sense the Earth's features as well as the data collected by specifically designed data collection platforms (DCP).[1]

1.2 The Alabama ERTS Project

The University of Alabama, with the participation of the Geological Survey of Alabama and the Marshall Space Flight Center, has undertaken a study of the feasibility of applying remotely sensed data to the management of natural resources and to the improvement of environmental quality in Alabama. The accomplishment of this purpose will require the following:

(1) Identification and education of users with regard to the potential benefits to be derived from space-acquired data.

(2) Timely interpretation and dissemination of beneficial information to ultimate users, especially policy makers and regulatory agencies.

(3) Analysis of whether or not information from remotely sensed data results in a significant improvement of the user's decision-making ability and actions related to management of natural resources and environmental quality.[2]

The overall objectives of the Alabama ERTS project are summarized in outline form in Table I. In addition, Tables II and III show, respectively, areas of application of ERTS data and professional people who could derive benefits from ERTS data.

Because water is one of the major natural resources and plays an important role in the development of other resources, particular emphasis is given to water resources both as to quantity and quality in the Alabama ERTS project.[3] Therefore, one of the primary purposes of the environmental phase of this project is to test the feasibility of using remotely sensed data in conjunction with ground truth data to monitor, predict, and manage water quantity and quality in our waterways.

There are several applications for this concept to the monitoring and management of environmental quality. One application is concerned with the fast and accurate acquisition of data necessary to meet the needs of water resource managers, which include both regulatory agencies and private industries.[4] Results from data collection platforms strategically placed in a water basin, together with satellite imagery, may be used to characterize environmental factors and provide means to record changes in environmental quality. In addition, the ERTS data from the DCP may be employed in monitoring environmental changes with regard to enforcing state and federal regulations. The collected data may be stored in an information system which would allow access to specific data according to the needs of the user.[2]

TABLE I

OBJECTIVES OF ALABAMA ERTS PROJECT[3]

A. TO DETERMINE THE APPLICABILITY OF REMOTELY SENSED DATA FROM ERTS FOR:

(1) LAND USE

(2) INVENTORY AND MANAGEMENT OF NATURAL RESOURCES

(3) IMPROVEMENT OF THE QUALITY OF ENVIRONMENT

B. TO DISSEMINATE INFORMATION IN FORMS MOST SUITABLE FOR ULTIMATE USERS:

(1) PUBLIC POLICY TECHNICIANS

(2) DECISION MAKERS

(3) PRIVATE INDUSTRIES

(4) PRIVATE CITIZENS

TABLE II

USES OF ERTS DATA[3]

FLOOD CONTROL	DISASTER DETECTION
SOIL STUDIES	DAMAGE EVALUATION
RESOURCE INVENTORY	SEDIMENT TRANSPORT
SURFACE WATER STUDIES	TRAFFIC STUDIES
MINERAL EXPLORATION	EROSION CONTROL
GROUND WATER STUDIES	IRRIGATION
ZONING	WATER TEMPERATURE STUDIES
GROWTH TRENDS	CROP CONDITIONS
RECREATION	SURVEYING AND MAPPING
MANAGEMENT	AIR QUALITY MANAGEMENT
PESTICIDE STUDIES	WATER QUALITY MANAGEMENT

URBAN AND REGIONAL PLANNING

TABLE III

POTENTIAL USERS OF ERTS DATA[3]

URBAN PLANNERS	CIVIL ENGINEERS
REGIONAL PLANNERS	CHEMICAL ENGINEERS
FORESTERS	AGRICULTURAL ENGINEERS
GEOLOGISTS	MINING ENGINEERS
ECOLOGISTS	GEOGRAPHERS
HYDROLOGISTS	LIMNOLOGISTS
AGRONOMISTS	ENTOMOLOGISTS
BIOLOGISTS	ARCHITECTS
PHYSICISTS	ARCHAEOLOGISTS
ASTRONOMERS	DEMOGRAPHERS
CHEMISTS	LAWYERS
AGRICULTURISTS	UNIVERSITY FACULTY MEMBERS

In order to monitor a water basin in an effective and optimum manner, it is necessary that the locations of the data collection platforms be selected such that measurements of water quality parameters at these locations will be indicative of water quality over the entire basin. This study is concerned with developing methodology for selection of these optimum monitoring sites as specifically noted in the objectives given below.

1.3 Objectives

The objectives of this study were:

(1) to develop the methodology, based upon a systematic investigation, for selection of desirable locations for placing remote sensing devices (data collection platforms) in a waterway such that the data collected will be indicative of the water quality over the entire basin.

(2) to select desirable locations for placing data collection platforms in a portion of the Black Warrior River basin.

(3) to develop a mathematical model which may be employed to predict water quality in the Black Warrior basin.

CHAPTER II

MONITORING SYSTEMS

2.1 Conventional Automated Monitors

Changes in water quality, such as those caused by storms, industrial spills, and flow changes from impoundments, often occur suddenly and affect the concentration of many substances of particular interest. For this reason, continuous monitoring of water quality is advantageous in situations where these abrupt changes are likely to occur. Because of the manpower and time requirement involved in standard manual sampling and analysis, testing in water pollution control work has been moving more toward instrumentation.

A typical installation utilizing a continuous, automated monitor is shown in Figure 1. Most automatic monitors have three basic components--sensor system, analyzer phase, and output phase. The sensing element, which is the part of the system in contact with the sample, may be either immersed in the stream or set in flow cells through which the sample is pumped. Because of advantages in design and maintenance, most systems use the flow cell principle; however, when the sensor is directly in the stream, the sample is not affected by pumping, temperature changes, or time of travel through the instrument.

The types of sensors currently available fall into several categories: (1) electrochemical sensors, (2) sensors based on colorimetric or

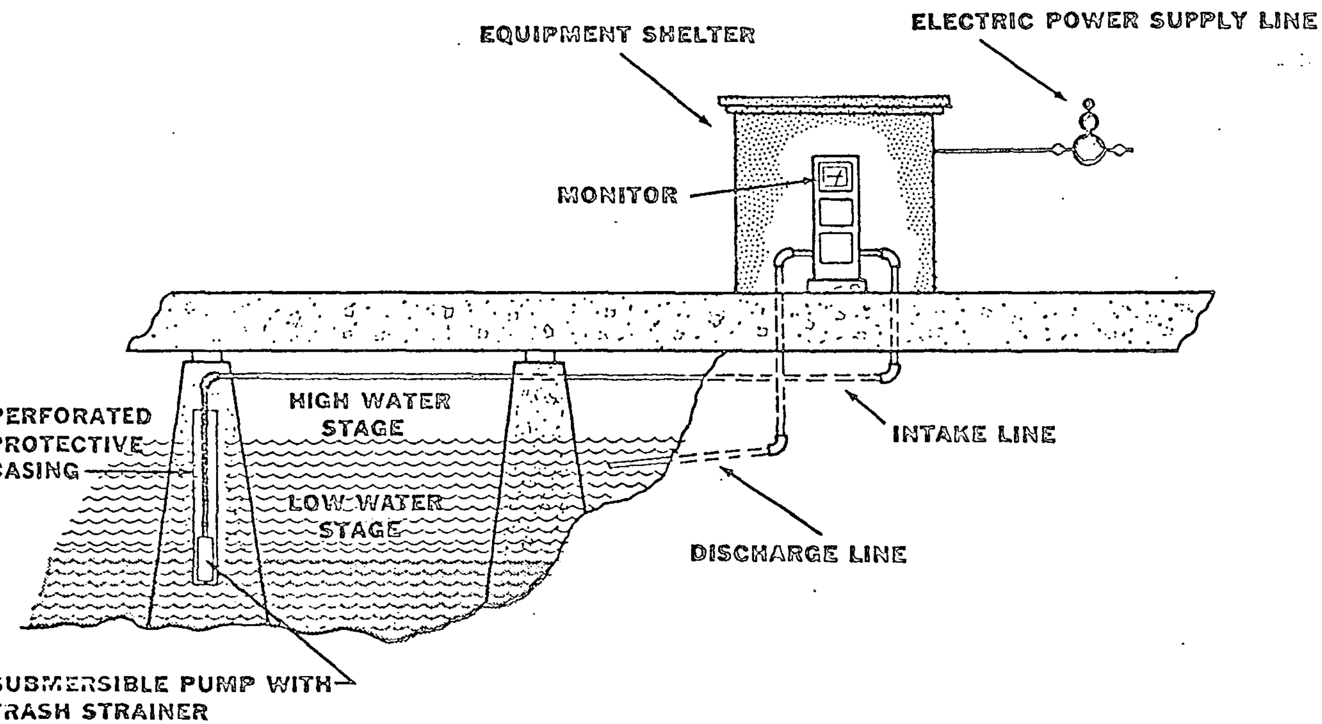


Figure 1. Conventional Monitoring Installation[5]

light-scattering measurements, (3) sensors measuring temperature through use of a thermocouple, and (4) sensors measuring physical parameters such as velocity.

The analyzer phase of the monitoring instrument converts the signal from the sensor into a voltage to apply to the output phase. The analyzer may be designed to receive signals from one or more than one sensing element.

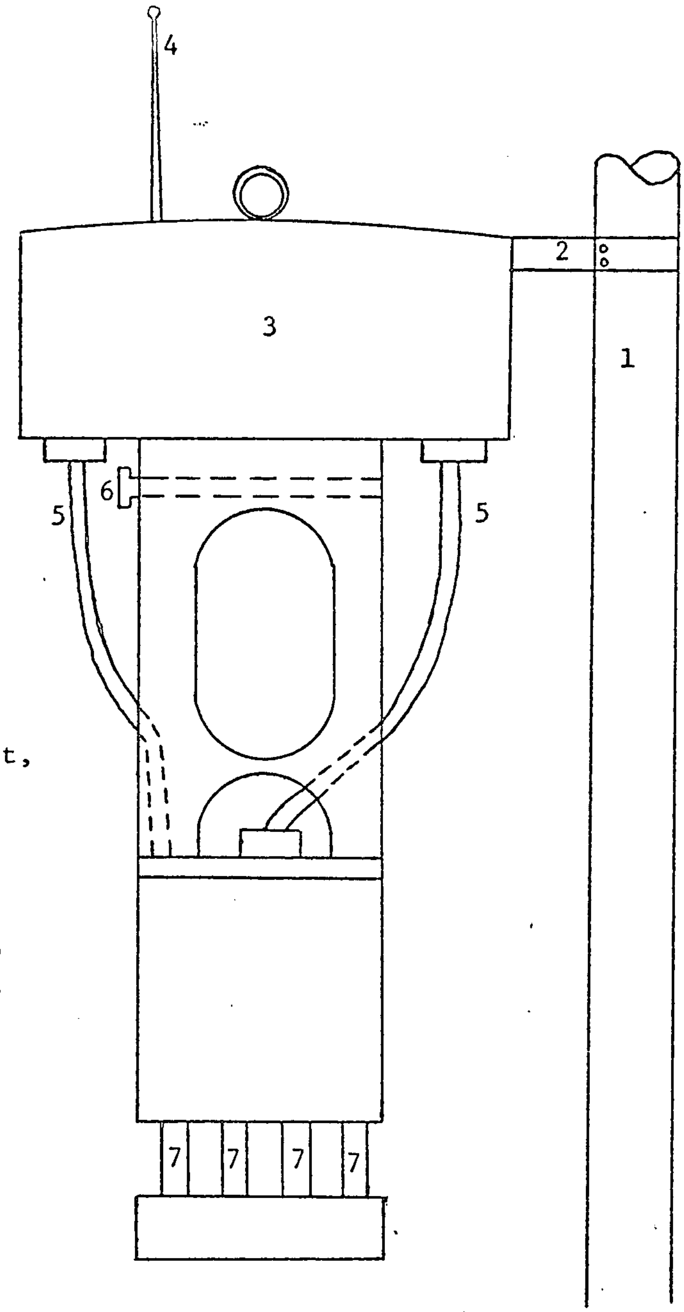
The output phase of the instrument presents the measured value in the necessary units--pH units, milligrams per liter, micromhos, etc.--and records it permanently. This component normally has a meter panel on the face of the instrument to indicate output to the recording devices.

Where a number of monitoring devices are interconnected to provide a simultaneous evaluation of water quality in a river system, a telemetry system to provide remote handling of the data has almost become a requirement due to the need for speedy collection and analysis of the data.[6]

2.2 Description of ERTS Data Collection Platforms

The instrumentation used in the ERTS program for monitoring water quality, while in some respects similar to conventional instrumentation, embodies some innovative features in its design and construction.

Figure 2 shows a sketch of one of the data collection platforms to be used in the Alabama ERTS project. Its primary components consist of the radio transmitter inside the upper housing, the antenna located on top of the housing, and the sensors, which are included in the lower



PRIMARY COMPONENTS:

1 - Metal Pole (support)

2 - Sliding Fastener

3 - Housing for Analyzer Unit, Battery, and Electronic Unit

4 - Antenna

5 - Connector from Sensor to Analyzer Unit in Housing

6 - Quick Release Pin

7 - Sensor

Figure 2. ERTS Data Collection Platform[7]

extremity of the DCP. The instrumentation of the DCP will be fastened to a metal pole which has been driven securely into the river bottom. The fastener will allow vertical movement of the instrument along the pole, facilitating its removal for recalibration and other servicing. The DCP will be submerged except for the antenna and a small portion of the housing, allowing monitoring at a five-foot depth. Another attractive feature of the sliding fastener mentioned above is that it will allow the DCP to float and maintain the five-foot monitoring depth regardless of changes in the water level.

The DCP will be one of three basic units in the overall data collection system, the other two being the ERTS satellite and the ground receiving station. As now planned, the DCP will be activated by a timer shortly before the satellite is due to pass over in any of several adjacent orbits within a line of sight of the DCP. The DCP will remain operational until the satellite has passed overhead, after which the instrument will be deactivated. The water quality measurements taken during this period of operation are immediately beamed to the satellite by means of a radio transmitter and antenna which are part of the DCP itself. Computers on board the satellite will correlate this data received from the DCPs with imagery taken at the same time by sophisticated scanners on board the satellite and transmit the data to the receiving stations on the ground.[7]

Two requirements regarding installation of the DCP are that it be (1) near the shore, where possible damage by contact with river traffic in the main channel will be minimized, and (2) in a position such that the line of sight to the satellite may be maintained. This latter requirement would exclude areas having high or overhanging cliffs on either bank of the river.

2.3 Comparison of the ERTS Data Collection Platforms with Conventional Automated Monitors

In describing both the conventional automated monitor and the DCP to be used in the ERTS program, several advantages of using the DCP system became apparent. The primary advantage of the DCP is that it allows immediate correlation of water quality data with imagery taken from the ERTS satellite, in order that a methodology might be developed for detecting the occurrence of significant changes in the quality of water. Another advantage is that this DCP data could be used for developing means of detecting changes in basin characteristics and the constituents of runoff from the ERTS imagery.

Another attractive feature of the DCP is that after the satellite comes down there is a possiblity that the DCP could be utilized in the same manner as the conventional automated monitor.

2.4 Parameters Monitored

In the selection of water quality parameters to be monitored, it is important to select those which would be of the most benefit to the ultimate users. It was decided that in the Warrior River basin the parameters dissolved oxygen, temperature, pH, and specific conductance would provide the most beneficial information for the management of basin water quality.[2] Table IV, which lists parameters according to frequency of usage in state water quality standards, indicates that, with the exception of conductance, which is used less than 20 percent of the time, the

TABLE IV

FREQUENCY OF PARAMETER USAGE IN WATER QUALITY CRITERIA OF STATE STANDARDS[6]

Uniform (100%)	Frequent (99-50%)	Infrequent (49-20%)	Rare (19-0%)
DO	Radioactivity	Arsenic	Bottom Deposits
pH	Public Health Service Drinking Water Stds.	Barium	Chromium (+3)
Coliform		Cadmium	Electrical Conductance
Temperature	Total Dissolved Solids	Chromium (+6)	Ammonia
Floating Solids (Oil-Grease)		Fluoride	Acidity
		Lead	Alkalinity
Settleable Solids		Selenium	CCE
Turbidity and/or Color		Silver	Hydrogen Sulfide
		Suspended Solids	Pesticides
Taste-Odor		Turbidity	Sodium
Toxic Substances		Chloride	Iron
		Copper	Plankton
		Nitrate	Foaming Substances
		Phenols	Boron
		Phosphate	Manganese
		Sulfate	Hardness
		Color	BOD
		Cyanide	MBAS
			Zinc

selected parameters are those uniformly used in formulating state water quality criteria. In view of the fact that state regulatory and planning agencies are anticipated to be one of the principal users of ERTS water quality data, the choice of these four parameters appears to be advantageous.

CHAPTER III

SELECTION OF THE WATER BASIN AREA

3.1 Background

The original plans for this study called for the use of ten DCPs in monitoring the water quality of several river basins on a statewide basis. Later developments indicated that the number of available DCPs would be reduced to the five now allotted to this portion of the Alabama ERTS investigation. Based on this reduction, it was felt that the investigation should be confined to a single river basin to avoid a thin coverage of a multiple basin area, where the data collected would be from relatively isolated and unrelated points. Also, simultaneous evaluation of water quality with ERTS imagery over a large geographical area would be less significant than that produced for a smaller and more extensively monitored area.[8]

3.2 River Basin Selected for Investigation

The sector of the Black Warrior River from river mile 385.0 to river mile 335.0 was chosen for evaluation in testing the utility of the DCP concept for monitoring water quality. Shown in Figure 3, this stretch of the river extends from the confluence of the Locust and Mulberry forks downstream to a point approximately three miles below Oliver Lock and Dam. These limits were selected, in part, because they cover all significant pollutional effluents received by the Black Warrior River from

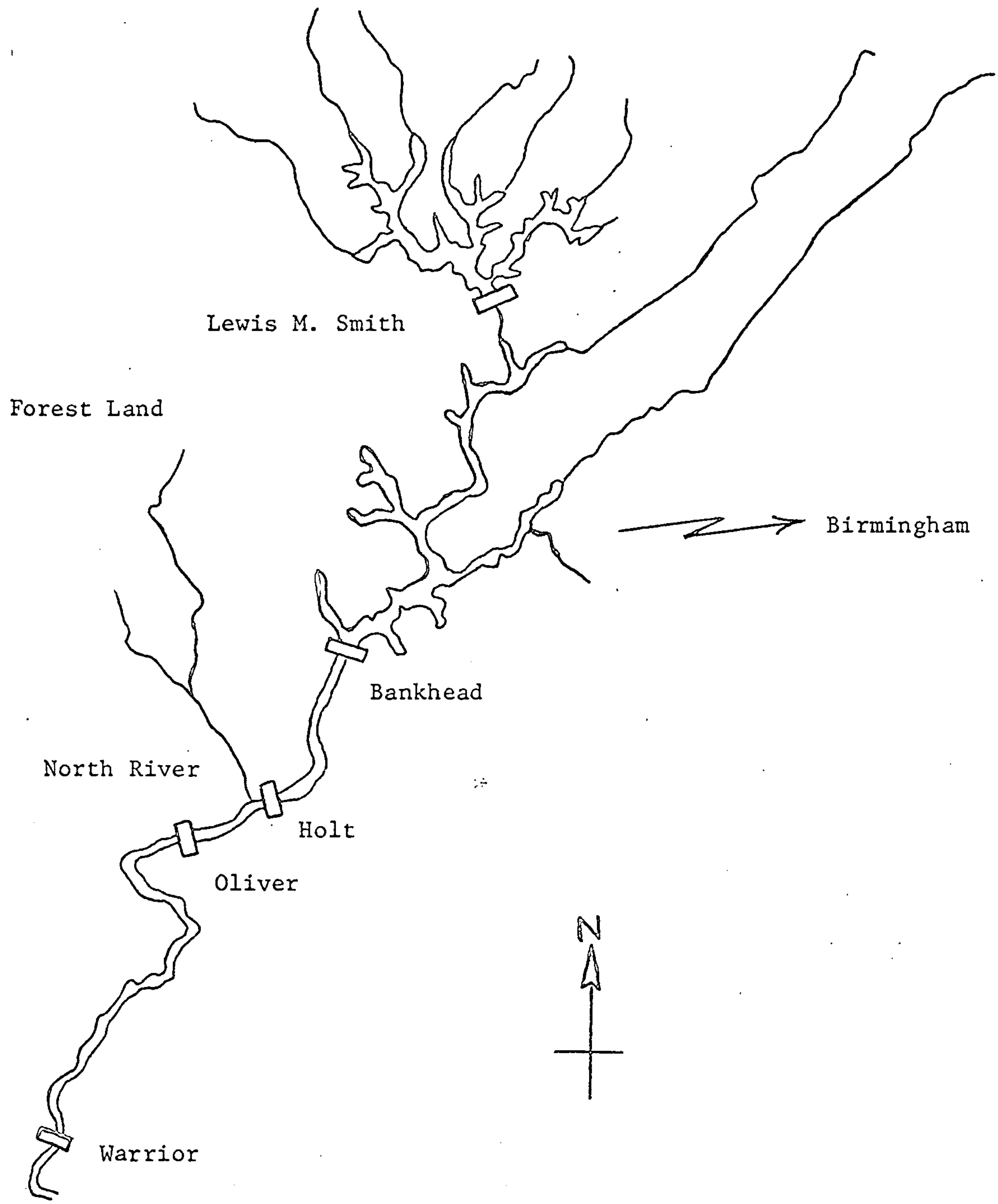


Figure 3. The Black Warrior River Basin

the highly industrialized area in the vicinity of Tuscaloosa. Another unique factor concerning this sector is that the relative quality of the water both upstream and downstream of these limits is good while portions of the area considered are grossly polluted, especially during the low flow periods occurring in the summer months.

The reasons for choosing the Warrior River Basin for the study are summarized as follows:

(1) overall convenience of the basin in regard to data collection and maintenance of DCPs to the primary investigating groups at The University of Alabama, the Geological Survey of Alabama, and Marshall Space Flight Center.

(2) relatively unrestricted use of the river as a receiving body for disposal of sewage and industrial wastes.

(3) location on the river of several major industries, such as chemical, petrochemical, iron products, coking, pulp and paper, and asphalt operations, which discharge wastewaters with varied constitutents.

(4) location of several dams and hydroelectric power generation facilities at Bankhead, Holt, and Oliver, which would allow the investigation of their effects on the quality of water in an impoundment.

(5) presence of both stratified and unstratified conditions in the reservoirs, primarily due to the deep, slow-moving waters in Bankhead and Holt pools and the shallow, swifter waters in Oliver and Warrior pools.

(6) presence of both relatively unpolluted waters, such as Bankhead Pool, and grossly polluted areas, allowing comparative modeling techniques for various degrees of water quality.

(7) potential for additional investigations, such as evaluating the moderating effect of a clean stream (Mulberry Fork) joining a relatively polluted stream (Locust Fork).

The above reasons for selecting the Black Warrior River point out the numerous advantages inherent in selection of this area for investigation during this part of the environmental phase of the Alabama ERTS project.

CHAPTER IV

REVIEW OF LITERATURE

Since the ERTS remote-sensing concept involving correlations of imagery taken from the satellite with water quality data obtained by the DCPs is new and unprecedented, reliance must be placed on previously reported methods for selection of DCP locations and for the development of stream quality models.

4.1 Dissolved Oxygen Models for Flowing Streams and Impoundments

The first dissolved oxygen model for predicting oxygen balance in a flowing stream was developed by Streeter and Phelps[9] in 1925. The formulas, which are based upon two velocity constants, describe the oxygen balance in a stream as a function of distance (or time) from a waste load discharge point. These two parameters are k_1, the deoxygenation velocity constant, and k_2, the reaeration velocity constant. These constants describe the activity in the stream in an all-encompassing fashion, with the effects of several known interacting factors such as photosynthesis and bottom deposits considered as being included in the k_1 and k_2 values.

Other investigators have proposed models which differ somewhat, but all employ the original Streeter-Phelps formulation as the basis of their work. Goodman[10] was one of these subsequent investigators who developed a mathematical model to apply to flowing streams containing no reservoirs and not influenced by estuaries. This particular effort toward water quality modeling was based on modifications of the original Streeter-Phelps equation and considered dissolved oxygen concentration as the principal criterion of stream quality. These equations determining changes in BOD and DO require input values for deoxygenation and reaeration velocity constants, settling out of BOD to bottom deposits, resuspension of BOD from bottom deposits, and oxygenation by photosynthetic processes.

More recent work involving modeling of flowing streams has been reported by the Texas Water Development Board. The result of this work was the development of a computer program called QUAL-I[11] that is capable of producing a time history and spatial distribution of not only BOD and DO but also temperature and as many as three minerals. This is accomplished within the framework of a completely-mixed, branching stream or canal system with multiple waste inputs and withdrawals. In addition, this agency has developed the DOSAG-I[12] program, which is used to simulate the spatial and temporal variations in BOD and DO under various conditions of temperature and headwater flow.

One of the more useful recent studies done on the subject of modeling dissolved oxygen was conducted by Pyatt,[13] who developed equations for predicting organic matter and DO deficit not only for a free-flowing stream but also for an impounded waterway. These formulations are based on the original Streeter-Phelps equations with added "error" terms to account for the usually omitted factors such as bottom deposits and photosynthesis which affect the deoxygenation and reaeration rates in a stream environment.

The modeling of the reservoir-type situation is particularly noteworthy since relatively few investigators have even attempted such a study. Due to the lack of previous knowledge in this particular area, complete mixing was assumed for the reservoirs, although this is not actually the case in most impoundments.

Churchill and Nicholas[14] also investigated the changes occurring in the quality of water during its passage through Tennessee River reservoirs and during long storage in impoundments. However, these studies were primarily observations in which no attempt was made toward developing generalized equations for predicting changes in impoundments.

4.2 Water Quality Monitoring Systems

Quite a number of investigating groups have undertaken to set up systems to monitor and control water pollution. Describing all of these in detail would be a formidable task; therefore, only the ones considered applicable to this study are reviewed.

McCormack and Perlis[15] developed a method of optimizing the number and locations of measurement stations needed for a particular monitoring program. In developing this procedure they applied theories of system optimization to a polluted stream model in which the primary dependent variable was dissolved oxygen. The stream models were subject to random variations and environmental changes. Measurement error was a function of the number and position of the measurements, the sample size, and the time between measurements. The developed policy minimized an integral-type function involving mean square error and actual measurement cost.

Other studies, which may not be directly concerned with optimizing locations of monitors, are strongly related to the use of water quality data in water resources management and therefore pertinent to the entire ERTS project. A Harvard research team[16] on the Lehigh River was the first group to conduct regional water resource management studies using systems analysis techniques. In recent years, both federal agencies and universities have used systems analysis on river basins, including water quality studies on both the Columbia and the Delaware river systems.

Another group to enter this field of basin management was the Ohio River Valley Water Sanitation Commission (ORSANCO)[17] which in 1960 built an automatic field monitor and a central receiving station to aid in management of water quality in the river basin. Later, more field monitors and data processing facilities were added to make up the integrated system now in operation.

Testerman[18] reported on a system for recording and transmitting digital data at a remote water quality monitoring station that is unattended. Signals from transducers, which measure water quality characteristics, are converted to digital signals and recorded on magnetic tape. This unit can be contacted from a central unit for playback of the day's recording with the transmitted data being recorded by teletype at the central station. The techniques developed in this study hold promise for making water quality measurements in remote areas and at numerous sites and reporting to one central station.

The United States Army Corps of Engineers[6] has also conducted an interesting study involving the control of impoundments to augment flow based on information reported by a monitoring station concerning dilution requirements.

CHAPTER V

DEVELOPMENT OF THE MODEL

5.1 General

The steps outlined in this chapter were undertaken to develop a technique which would ultimately lead to the selection of the desirable sites for placing the ERTS data collection platforms. It was intended that the methodology developed in this study would find general application for the placement of remotely-sensed monitoring stations.

Since dissolved oxygen is normally considered to be the most important parameter in defining water quality, it was decided that the procedure for selecting DCP monitoring sites would be oriented toward locating the critical dissolved oxygen concentrations in the river basin. For this reason, the modeling technique considered in this study was centered around simulating the dissolved oxygen concentrations normally found in the river.

While dissolved oxygen is considered to be the principal parameter of interest, the additional parameters of pH, temperature, and conductivity are also to be monitored. Factors such as mine drainage and runoff from agricultural lands, which would affect these latter three parameters, were also considered in developing the methodology for selecting the monitoring sites.

In deciding to select locations of monitoring sites based on the most sensitive points for dissolved oxygen, it was felt that the major effects on the other three parameters could also be detected at these same locations. The opposite of this, that is, selecting locations based primarily on monitoring pH, temperature, and conductivity would not necessarily produce locations of meaningful dissolved oxygen concentrations. The reasoning here was that while dissolved oxygen content is very much dependent on time (and therefore distance), factors that would be indicative of changes in pH, temperature, and conductivity, such as dissolved solids content, are largely independent of time of flow, depending instead on the amount of dilution received.

For the reasons discussed above, the technique developed in this study does not simulate pH, temperature, or conductivity, but it does include the capability of receiving inputs for factors affecting these parameters should it become desirable to include these values in modeling studies.

5.2 Factors Affecting Oxygen Balance in Streams

The factors responsible for the occurrence of oxygen variations in streams as well as for the magnitudes of these variations are listed by Goodman[10] as: (1) deoxygenation, (2) reaeration, (3) algal activity, (4) benthal demand, (5) settling and resuspension of BOD, (6) temperature, (7) streamflow, and (8) sunlight. The factors which serve to effect a decrease in dissolved oxygen concentration are deoxygenation due to oxidation of organic matter, benthal demand (bottom deposits), resuspension of organic matter having an oxygen demand, an increase in temperature of the water, and a decrease in streamflow. Conversely, those factors which would contribute toward an increase in the dissolved oxygen are reaeration, the photosynthetic activity of algae in combination with sunlight, settling of organic matter having an oxygen demand, a decrease in temperature, and the diluting effect of an increase in streamflow. In Figure 4 a diagram is presented depicting activities which would exert some measure of influence on the BOD and DO systems of the total river environment.

5.3 Streeter-Phelps Equation

The first attempt to mathematically relate the factors affecting the oxygen balance in a natural stream was performed in 1925 by Streeter and Phelps.[9] These investigators combined all the factors adversely affecting dissolved oxygen into a basic deoxygenation equation, while those factors contributing to an increase in dissolved oxygen were combined into a basic reaeration equation. These two equations are shown below in both their differential and their integrated forms.

$$\frac{dL}{dt} = -k_1L \tag{1}$$

$$L(t) = L_a(e^{-k1t}) \tag{1a}$$

$$\frac{dD}{dt} = -k_2D \tag{2}$$

$$D(t) = D_a(e^{-k2t}) \tag{2a}$$

In the above equations L(t) and D(t) are, respectively, the concentration of organic matter remaining at time t and the dissolved oxygen deficit at time t. The terms La and Da are, respectively, the concentration of organic matter and the dissolved oxygen deficit at t = 0, while

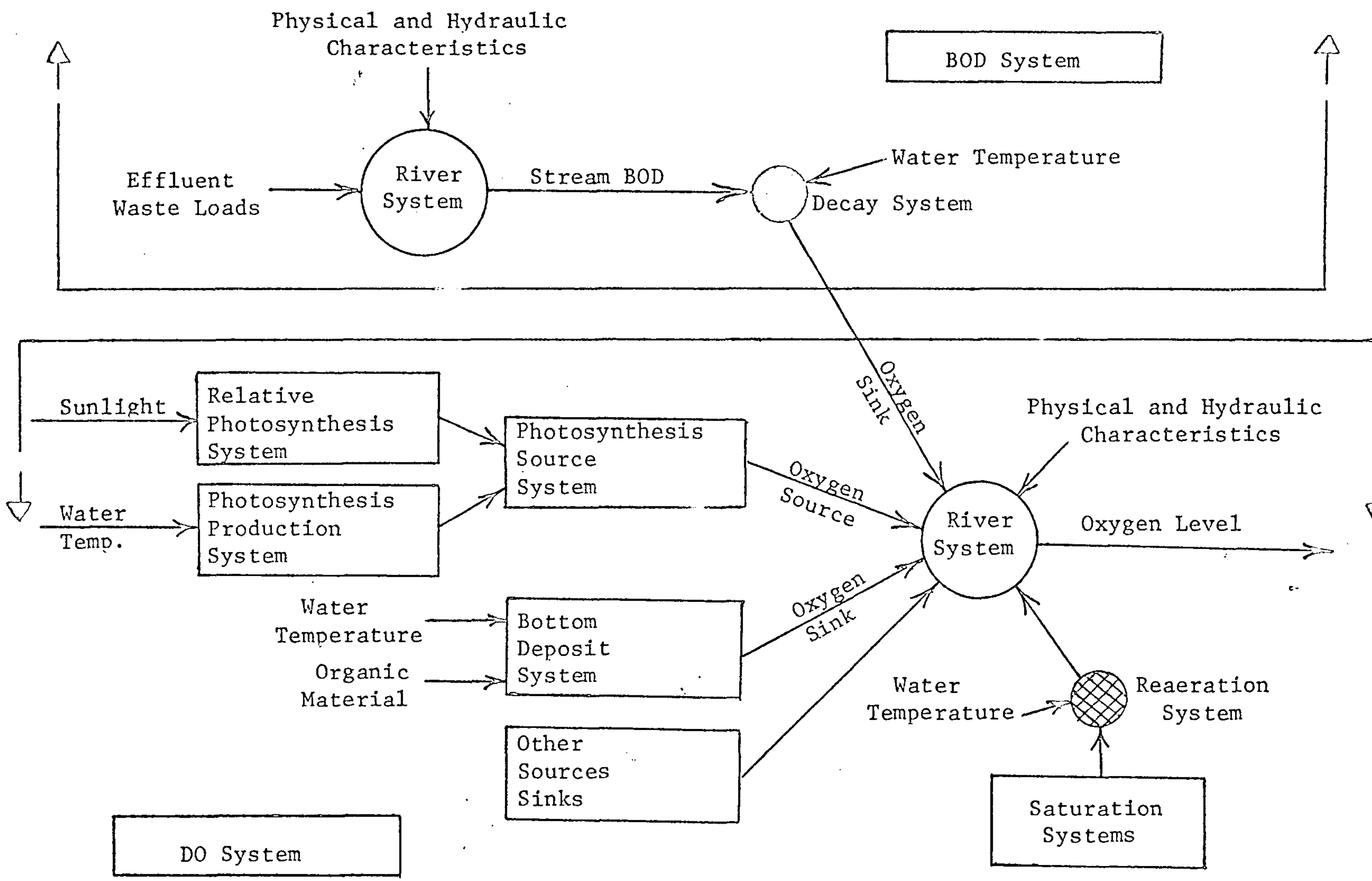


Figure 4. Factors Affecting Dissolved Oxygen

k_1 and k_2 are, respectively, the overall deoxygenation and reaeration rate constants.

Equations (1a) and (2a) were combined to give the well-known dissolved oxygen sag equation shown below in Equation (3).

$$D(t) = \frac{k_1 La}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) + Da(e^{-k_2 t}) \qquad (3)$$

This equation, developed for the case of a free-flowing, non-impounded stream, has remained the basis of nearly all water quality research related to dissolved oxygen.

5.4 Modifications of the Original Streeter-Phelps Equation by Pyatt

While the original dissolved oxygen sag equation developed by Streeter and Phelps has remained largely unchanged, some investigators such as Pyatt[13] have attempted to make refinements, particularly in the area of altering the rate constants to account for factors such as photosynthesis and bottom deposits in some manner other than grossly combining them all together in the k_1 and k_2 rate constants.

Pyatt has proposed accounting for the additional factors in the form of certain "error" terms. He has added a factor r, the deoxygenation error term, to the general deoxygenation equation to obtain:

$$\frac{dL}{dt} = -k_1 L + r \qquad (4)$$

which, when properly integrated, gives:

$$L(t) = (La - \frac{r}{k_1})\, e^{-k_1 t} + \frac{r}{k_1} \qquad (5)$$

Similarly, Pyatt has added a factor s, called the reoxygenation error term, to the dissolved oxygen sag equation to obtain:

$$\frac{dD}{dt} = k_1L - k_2D + s \qquad (6)$$

which, when integrated gives:

$$D(t) = \left[\frac{k_1L_a}{k_2-k_1} - \frac{r}{k_2-k_1}\right](e^{-k_1t} - e^{-k_2t})$$

$$+ \frac{1}{k_2}(r+s)(1-e^{-k_2t}) + D_a\, e^{-k_2t} \qquad (7)$$

The error terms r and s are usually set equal to 0.005. All other variables in Equations (4) through (7) are as previously defined.

One drawback to the use of Equations (5) and (7) is that they are limited to use with a flowing stream. Recognizing this limitation, as well as the fact that most streams are now regulated to some extent, Pyatt sought to develop equations for the concentration of organic matter and the DO deficit in an impoundment. His efforts resulted in the following equations:

$$L(t) = L_o\, e^{-At} + \frac{ZL_{in}}{A}(1-e^{-At}) \qquad (8)$$

$$D(t) = \left[D_o - \frac{ZD_{in}}{B} + \frac{k_1}{A-B}\left(L_o - \frac{ZL_{in}}{B}\right)\right] e^{-Bt}$$

$$+ \left[\frac{k_1}{B-A}\left(L_o - \frac{ZL_{in}}{A}\right)\right] e^{-At} + \frac{Z}{B}\left(D_{in} + \frac{k_1L_{in}}{A}\right) \qquad (9)$$

where the variables are defined as follows:

L_o = concentration of organic matter in the reservoir before the input of waste flow from upstream

D_o = dissolved oxygen deficit in the reservoir before the input of waste flow from upstream

L_{in} = incoming concentration of organic matter

D_{in} = incoming dissolved oxygen deficit

W = outflow $\div$ volume

Z = inflow $\div$ volume

k_3 = deoxygenation rate constant for sludge deposits on bottom of reservoir

$A = k_1 + k_3 + W$

$B = k_2 + W$

One limitation of Equations (8) and (9) is that complete mixing in the reservoir must be assumed, although this is often not the actual case. Even with this built-in source of error, which would probably cause predicted values of dissolved oxygen concentrations to be slightly lower than those actually found, these equations have been found to be particularly useful in simulating the dissolved oxygen profile of a stream. Pyatt utilized these equations in simulating the DO profile in an actual river basin containing impoundments, showing that the formulae developed in his study do provide accurate results.

5.5 Application of Formulas to Warrior River

When considering the stretch of the Warrior River with which this phase of the Alabama ERTS project is concerned, it became apparent that no single equation can be applied over the entire run of the river from the confluence of the Locust and Mulberry forks to several miles below Oliver Lock and Dam.

This area of the river, which includes all of the Holt and Oliver pools and portions of the Bankhead and Warrior pools, is, in the strictest sense, impounded over its entire length, suggesting that Equations (8) and (9), developed for use with impoundments, should be used for this entire stretch of the river. This would certainly hold true for the Bankhead and Holt pools, which, in addition to containing the deep, slow-moving waters characteristic of impounded streams, are also regulated entirely by the release of water from Bankhead and Holt dams. However, in the case of Oliver Pool and the portion of the Warrior Pool included in this study, the waters are shallower and faster-moving than in Holt and Bankhead pools upstream. Another factor to be considered is that Oliver Dam is a free-flow dam with the water flowing over the crest. As a result, these waters are subjected to much less regulation than that found at Bankhead and Holt dams, which are not of the free-flow type.

For the reasons enumerated above, it was felt that Bankhead and Holt pools are impoundments requiring the use of Equations (8) and (9) for dissolved oxygen simulation. However, the Oliver and Warrior pools, though technically impoundments, more nearly approach the conditions of a flowing stream, and warrant the use of Equations (5) and (7) which were developed for free-flowing conditions.

It should be emphasized that this step is of paramount importance, requiring careful consideration of the stream under investigation before selecting the appropriate equations for use in simulating the dissolved oxygen profile.

5.6 Reach Concept Applied to the Model

Due to an absence of industries and other such inputs along the impoundments modeled by Pyatt, each of the impounded areas was considered as one reach or segment having no subdivisions. This approach lacked sufficient detail to model a complex basin such as the Warrior; however, the modeling equations developed by Pyatt can be applied to the Warrior River by subdividing each impoundment into smaller reaches that are capable of describing additional inputs.

This concept essentially involves separating the entire length of the river under consideration into a number of smaller reaches, such that each reach contains only one input, if any, and also to insure that the physical characteristics of the river remain the same throughout each individual reach.

In order to follow the above guidelines, a new reach is begun whenever one of the following events or structures is encountered:

(1) entrance of a major tributary

(2) the discharge of an industry or a domestic treatment facility

(3) an industrial withdrawal

(4) a dam or other flow-controlling structure.

The first three categories are necessary in order to reflect changes in the quality of water downstream that result from the input of a major tributary or an industrial discharge or withdrawal. The fourth category is necessary due to the nonavailability of a technique for predicting the dissolved oxygen and organic matter below a dam based on the values of these same variables above the dam. A regression method was employed in this study using observed values of organic matter and dissolved oxygen both above and below the dams; however, the correlation coefficient was too small to warrant placing much confidence in the calculated line of best fit through the data. As a result, the alternative is that a new reach be created at each dam, with observed values of organic matter and dissolved oxygen input into the model below each dam.

This inability to simulate the effect of a dam requires that the model developed herein re-start the simulation process at the upstream end of each impoundment, leaving a gap in the simulated profile at each of the dams along the river.

5.7 Necessary Input for Each Type of Reach

The four criteria outlined in Section 5.6 for designating a new reach result in seven different types of reaches that might be encountered, with the following distinguishing characteristics:

(1) SD--Stream Discharging into the river in a polluted condition

(2) SDH--Stream Discharging into the river and containing High-quality water

(3) R--Restriction to flow, such as a dam or other flow-controlling structure (this reach is normally given a length of 0.6 mile)

(4) N--No input (reach occurs immediately below a dam and is designated as a new reach so that BOD and DO values may be input at downstream end of type R reach)

(5) ID--Industry Discharging into the river (sewage treatment facilities also placed in this category)

(6) IW--Industry Withdrawing water from the river

(7) IWC--Industry Withdrawing water from the river very Close to the discharge point (this reach given a length of zero yet still designated as a new reach in order to remain separated from the discharge)

Due to the differing characteristics of the input to each of the reaches (withdrawal is considered as a negative input), each type of reach will require that different data be input to the model in order that the effect of that input might be properly evaluated. Table V

TABLE V

INPUT DATA REQUIRED FOR EACH TYPE OF REACH

Type of Reach	Reach Number	Month	Upstream R. M.	Downstream R. M.	Input Flow	Intake Flow	Release Flow	River Temperature	Temp. of Input	BOD_5 Input	BOD_5 Downstream End	DO Input	DO Downstream End	$k_1(20)$ Input (Base 10)	$k_1(20)$ River (Base 10)	Average Width	Average Depth
SD	X	X	X	X	X			X	X	X		X		X		X	X
SDH	X	X	X	X	X			X	X			X				X	X
R	X	X	X	X			X	X			X		X		X	X	X
N	X	X	X	X	X			X							X	X	X
ID	X	X	X	X	X			X	X	X		X		X		X	X
IW	X	X	X	X		X	X									X	X
IWC	X	X	X	X		X											

consists of a summary of the data that would be needed to sufficiently characterize the input for each of the seven types of reaches.

5.8 Division of Warrior River into Reaches

Following the outline set forth in the previous sections for the establishment of new reaches, the section of the Warrior River from river mile 385.0 to river mile 335.0 was segmented into 25 different reaches to be considered in simulating the dissolved oxygen profile of the river. Table VI contains a listing of these 25 reaches as well as upstream and downstream boundaries and the major input for each reach.

The actual river mile locations for these reaches were obtained from navigation charts of the Warrior River published by the Corps of Engineers.[20] It should be pointed out that the numbering convention used with the simulation technique employed in this study involves numbering reaches at the upstream end of the stretch under consideration and proceeding downstream.

Another convention adopted in this study is, where possible, to subdivide the river such that the type R reaches begin 0.5 mile above the dam and end 0.1 mile below the dam. The reasoning here is that those conditions which would set apart the waters around a dam from waters in other sections of the river are: (1) large bottom deposits in the forebay, extending perhaps as far as 0.5 mile above the dam, and (2) swift tailrace currents, whose velocities might be maintained for a distance of 0.1 mile below the dam.

In some instances, however, the above policy cannot be kept. Such is the case around Oliver Lock and Dam, where to extend the reach 0.5 mile above the dam would include the discharge from the Northport sewage

TABLE VI

REACHES OF THE WARRIOR RIVER USED IN
SIMULATION OF DISSOLVED OXYGEN

Reach	Upstream R. M.	Downstream R. M.	Input
1A	385.00	382.00	Locust & Mulberry Forks
2A	382.00	367.50	Valley Creek
3A	367.50	366.00	Yellow Creek
4A	366.00	365.40	Bankhead Lock & Dam
5A	365.40	361.50	None
6A	361.50	347.50	Davis Creek
7A	347.50	346.90	Holt Lock & Dam
8A	346.90	346.30	None
9A	346.30	345.70	Hurricane Creek
10A	345.70	345.70	Reichhold Chemical Co. Intake
10B	345.70	345.20	Reichhold Discharge
10C	345.20	344.40	A. B. C. Discharge
11A	344.40	344.40	Intake for Warrior Asphalt Co. & Empire Coke Co.
11B	344.40	344.39	Warrior Asphalt Discharge
11C	344.39	343.70	Empire Coke Co. Discharge
12A	343.70	343.50	North River
13A	343.50	343.00	Central Foundry Discharge
14A	343.00	342.50	Gulf States Intake
15A	342.50	341.60	Gulf States Discharge
16A	341.60	338.41	Tuscaloosa WTP Discharge
17A	338.41	338.39	Northport STP Discharge
18A	338.39	338.10	Oliver Lock and Dam
19A	338.10	337.00	None
20A	337.00	336.70	Hunt Oil Co. Intake
21A	336.70	335.00	Hunt Oil Discharge

treatment plant, in which case the requirement specifying only one input for each reach could not be met. To circumvent this problem, the treatment plant effluent was included in a reach of length 0.02 mile and the reach containing the dam was restructured so as to extend 0.3 mile above the dam and 0.1 mile below the dam. This solution provided that each of the two reaches would contain only one input.

5.9 Additional Equations Used

In developing a method for simulating the dissolved oxygen profile of a stream, the most important equations are those which actually predict the concentration of organic matter and the dissolved oxygen deficit. However, there are quite a number of other formulae utilized in providing input values to the final equations. These supporting equations are briefly described in the following sections.

5.9.1 Velocity Rate Constants

The three rate constants are comprised of the biodegradation coefficients k_1 and k_3 and the reaeration coefficient k_2. Commonly, the value of k_1, the constant pertaining to deoxygenation of suspended organic matter, is obtained as the slope of a semilog plot of organic matter remaining versus time. However, in quite a few instances during this study, when any BOD measurements at all had been taken, they usually consisted only of BOD_5 and BOD_{20} (L_a). In such cases the value of k_1 (base 10) was found by utilizing Equation (10):

$$BOD(t) = L_a \, (1-10^{-k_1 t}) \qquad (10)$$

which could be modified to the form of Equation (11).

$$k_1 = -\frac{1}{t} \log \left(1 - \frac{BOD(t)}{L_a}\right) \qquad (11)$$

In those cases where no BOD measurements had been taken by some of the industries, the author was forced to rely on some typical k_1 values given by Eckenfelder[21] for certain types of industrial wastes.

According to Pyatt[13] the value of K_3, the deoxygenation rate constant for bottom deposits in reservoirs, can be safely assumed to equal 0.005.

Quite a few empirical formulas have been developed for calculating k_2, the reaeration coefficient. Most are of the general form:

$$k_2 = \frac{CV^m}{d^n} \qquad (12)$$

Where V is the mean velocity, d is the mean depth, and C, m, and n are coefficients varying according to the use of each investigator.

The particular formula providing best results with a certain stream varies according to the characteristics peculiar to that stream. Results obtained in this study indicated that the equation developed by O'Connor and Dobbins[22]:

$$k_2 = \frac{12.90_V{}^{0.5}}{d^{1.5}} \qquad (13)$$

provided the most accurate values for k_2 in the Warrior River.

5.9.2 Corrections for Temperature

All of the above methods for calculating the velocity rate constants result in values accurate only at a temperature of 20 °C and, consequently, these values must be adjusted to the temperature of the water:

$$k_1(T) = k_1(20) \left[1.047\right]^{T-20} \qquad (14)$$

$$k_2(T) = k_2(20) \left[1.0159\right]^{T-20} \qquad (15)$$

$$k_3(T) = k_3(20) \left[1.047\right]^{T-20} \qquad (16)$$

In addition, the value of the ultimate BOD (L_a) must be corrected to the proper temperature:

$$L_a(T) = L_a(20) \left[0.02T + 0.6\right] \qquad (17)$$

In each case, Equations (14) through (17) represent the commonly used methods of correcting that particular parameter for temperature.[12]

5.9.3 Dissolved Oxygen Saturation

In order to determine the dissolved oxygen deficit in each reach of the river, it was necessary to know the saturation concentration of dissolved oxygen for the water in the main stream of the river as well as in the inputs of various tributaries and industrial wastes.

Quite a few references contain tables showing the saturation values of DO at various temperatures; however, in a simulation technique, the saturation values are needed in an equation form which is more easily adaptable to computer programming. The particular empirical formula employed in this investigation for calculating the saturation concentration of dissolved oxygen in water at a certain temperature was developed by TVA[23] and is shown below:

$$DO_{sat} = 14.65 - 0.41\ T + 0.008\ T^2 - 0.00008\ T^3. \qquad (18)$$

5.9.4 <u>Corrections for Changes in Flow</u>

As each new reach is encountered and the particular input for that reach is added to the flow from the reach immediately upstream, it was necessary to correct values of k_1, dissolved oxygen deficit, and concentration of organic matter for the mixed flow. The dilution method is employed in each case:

$$k_1 = \frac{k_1\ Q_{up} + k_1\ Q_{in}}{Q_{up} + Q_{in}} \qquad (19)$$

$$D = \frac{D\ Q_{up} + D\ Q_{in}}{Q_{up} + Q_{in}} \qquad (20)$$

$$L_a = \frac{L_a\ Q_{up} + L_a\ Q_{in}}{Q_{up} + Q_{in}} \qquad (21)$$

where Q_{up} is the flow leaving the reach immediately upstream and Q_{in} is the additional flow entering at the head of the particular reach under consideration.

CHAPTER VI

COLLECTION OF DATA

6.1 General

As previously stated, the primary purpose of this investigation was to locate the optimum monitoring sites for DCPs based upon critical dissolved oxygen concentration levels. The most promising technique to be employed for meeting this objective appeared to be a simulation of the dissolved oxygen profile of the river. It became evident that the period of the year which would present the lowest, and therefore most critical, values for dissolved oxygen would be the summer months of June through September, when the volume of flow is lowest and the temperature of the water is highest. It also appeared logical that the simulation technique and subsequent selection of DCP sites should be based upon the critical monthly average values for dissolved oxygen rather than upon critical daily values, since the monthly values are less subject to variations with respect to location that would normally be encountered with daily values. In addition, the data collected was obtained during the months of the previous summer, in order to assure that the data reflected any recent developments which might cause changes in the water quality of the river.

The nature of a study of this type requires the acquisition of large amounts of data for many parameters in order to characterize adequately the quality of the water in a river and in the major inputs. Many sources of information were investigated in searching for the data needed to develop the model. Information was obtained from interviews with representatives of the various industries, STORET, the Environmental Protection Agency's data acquisition system, and river surveys conducted by Alabama Power Company[24] and Gulf States Paper Corporation.[25]

It was hoped that STORET, a computer-oriented system devised by EPA for storage and retrieval of water quality data,[26] would be one of the principal sources of information. However, as a result of studying a report by Miller and Walters[27] on the use of STORET in water quality management and gaining some experience with the mechanics of using the system, it was concluded that the data available for the Warrior River was not recent, and therefore of little value in providing input to the model.

The remaining sections of this chapter are devoted to a general discussion of the sources of information resorted to in the search for each type of input data. A detailed listing of the data sources and all data gathered for each reach of the river is presented in Appendix II.

6.2 Velocity Rate Constants

Values of k_1, the overall deoxygenation constant, are necessary for each input of industrial waste or discharge from a polluted stream, as well as k_1 values for the stream flow below each of the dams on the river. The k_1 values immediately below the dams were obtained from BOD_5 and BOD_{20} values measured at these locations by Gulf States Paper Corporation during their summer river surveys.[25] In those cases where BOD_5 and BOD_{20} values were obtained by some of the industries on the river, such as at Empire Coke Company,[28] k_1 values were obtained through interviews with representatives of the particular industry. When such values were not known, typical k_1 values given by Allen and Bodenheimer[29] for paper mill waste and by Eckenfelder[21] for other types of waste were assumed to apply for the industries in question.

The reaeration rate constant for each reach was computed by the O'Connor-Dobbins formula given in Section 5.9.1, while values for the other constants--k_3, r, and s--were all assumed to be 0.005.[13]

6.3 Dissolved Oxygen and BOD in the River and its Tributaries

The major portion of the data for the parameters was obtained from the previously mentioned river quality surveys conducted during the summer of 1972 by Gulf States Paper Corporation[25] and Alabama Power Company.[24] Additional information was obtained from two publications by the Geological Survey of Alabama pertaining to stream quality.[30,31]

6.4 Industrial Withdrawals and Discharges

The primary source of data on withdrawals from the river for use by industries was an interview with Horn[32] followed by a perusal of the discharge permits on file with the Alabama Water Improvement Commission.

Data concerning the quantities and characteristics of the wastes discharged by the various industries were largely gathered from personal contacts with representatives of the industries--Fuller,[25] Davis,[28] Woods,[33] Witherspoon[34] and Sandifer[35]--while some additional data was obtained from the AWIC files and from historical data tabulated by McClure.[36]

6.5 Flow Rates

Principal sources of data regarding average rates of flow in the Warrior River were provided by Bowers[37] and by an impact study covering the effect of the Holt Dam on the water quality of the river.[24]

Information concerning rates of flow in the tributaries to the Warrior River was found in the USGS publication of flow data in Alabama for 1971[38] and in two publications of a similar nature which were released by the Geological Survey of Alabama.[31, 39] Information on discharge rates from the Tuscaloosa Water Treatment Plant were obtained from records kept at the plant.[40]

6.6 Water Temperatures in the River and its Tributaries

Data regarding temperatures of the water in the river were found to be plentiful in the previously noted river quality surveys conducted by Alabama Power Company[24] and Gulf States Paper Corporation[25] during the summer of 1972. Similar data for the tributaries were found in Circular 36,[30] a publication by the Geological Survey of Alabama regarding surface water quality in Alabama.

6.7 Cross-Sectional Areas

The only recorded measurement of cross-sectional area of the Warrior River was taken above Oliver Lock and Dam by the USGS.[38] Judging from values of width and depth given at this section, it appeared that a trapezoidal cross-section could be assumed for the river with the top width approximately twice the bottom width at that particular section.

Since no measurements of cross-sectional area were taken at other locations and also as there was a lack of information indicating the general shape of cross-sectional areas, the trapezoidal shape was assumed to apply over the entire stretch of the river considered in the study. Based on this assumption, the area of each reach was calculated by the following equations:

$$A = d/2(W_T + 1/2\ W_T) \tag{22}$$

which simplifies to:

$$A = 3/4 \times d \times W_T \tag{22a}$$

where A is the cross-sectional area, d is the mean depth, and W_T is the width of the water surface.

Values of the width at the water surface at normal pool elevation were scaled off navigation charts of the river published by the Corps of Engineers.[20]

Mean depth for each reach was taken as the difference between normal pool elevation in the particular reservoir containing that reach and the elevation of the river bottom in the reach. Normal pool elevations were taken from a pamphlet published by the Corps of Engineers[41] on the Black Warrior and Tombigbee rivers. Elevations of the river bottom for each reach were taken from information provided by Bowers.[37]

CHAPTER VII

DISCUSSION OF RESULTS

7.1 Comparison of Simulated and Observed DO Profiles

The results of applying the developed simulation technique to the Warrior River are shown in Appendix I in a tabular form printed by the computer program developed by the author for this model. In order to facilitate evaluation of these results, the simulated dissolved oxygen values in Tables VII through X of Appendix I were plotted in Figures 5 through 8 and compared with the profiles based on observed conditions in the same stretch of the river. These measured values of dissolved oxygen were taken from the river surveys conducted by Alabama Power Company[24] and Gulf States Paper Corporation.[25]

Based upon a visual comparison of the simulated and observed profiles, the results, which showed an error of less than 10 percent in most places, indicated that the developed model does provide acceptable accuracy in the prediction of dissolved oxygen content of the river. Some factors contributing to the differences between observed and simulated profiles were: (1) the highly variable nature of dissolved oxygen content in a stream, (2) the assumption of complete mixing used by Pyatt in developing his dissolved oxygen prediction equations for impoundments, and (3) the errors inherent in the measured values, which are monthly averages of observed values at one point in the cross-section

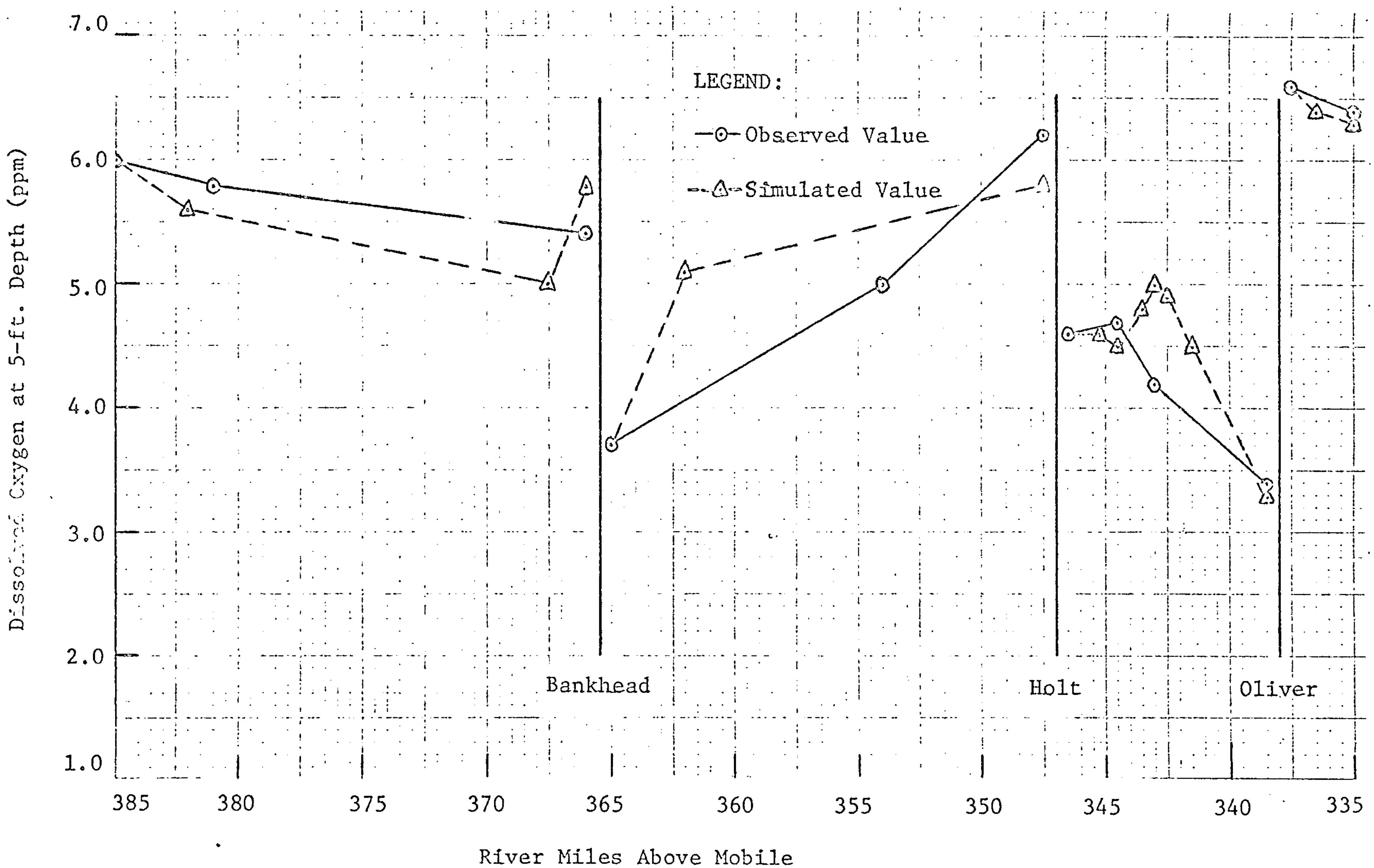


Figure 5. Dissolved Oxygen Profiles of Warrior River (June, 1972)

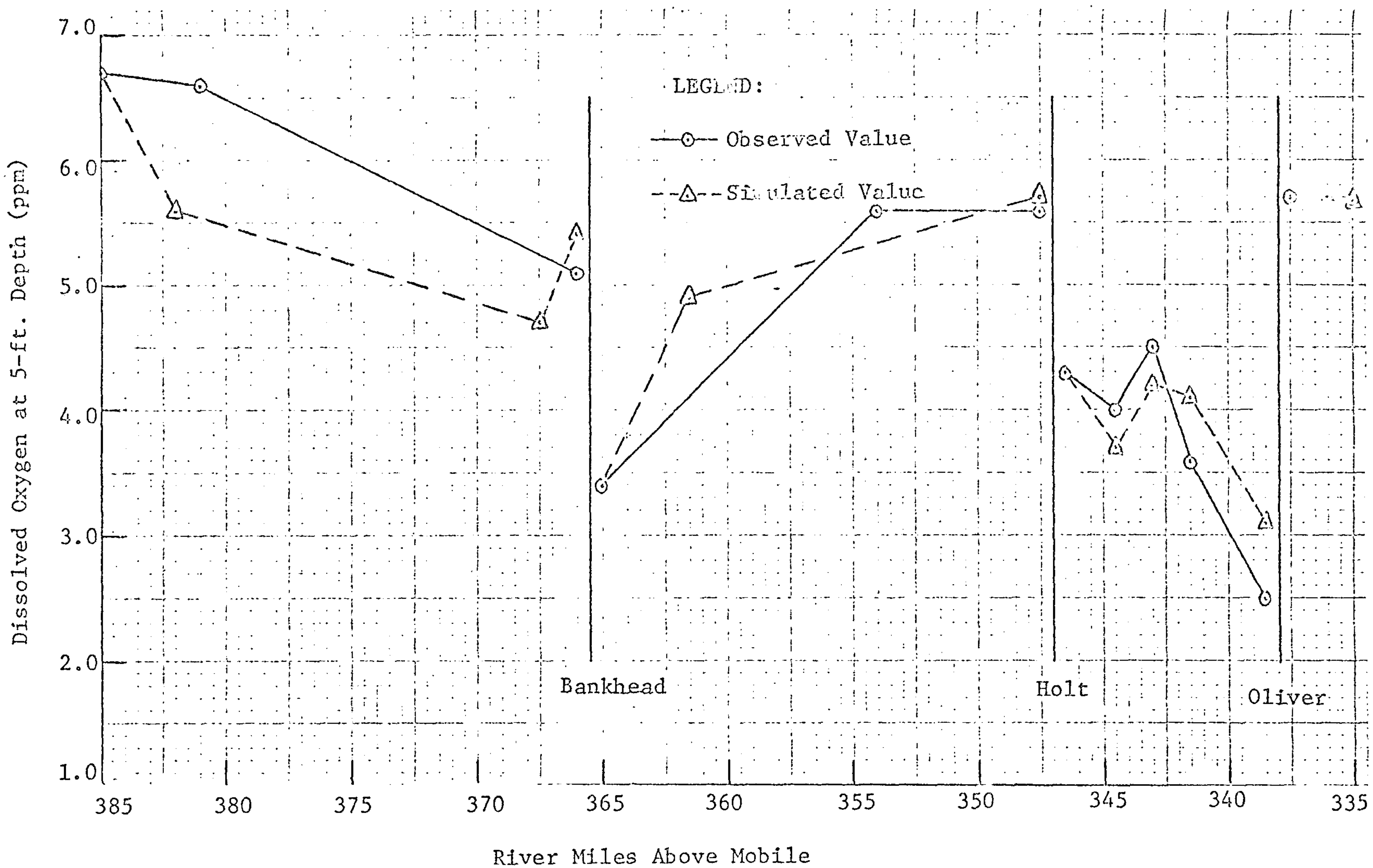


Figure 6. Dissolved Oxygen Profiles of Warrior River (July, 1972)

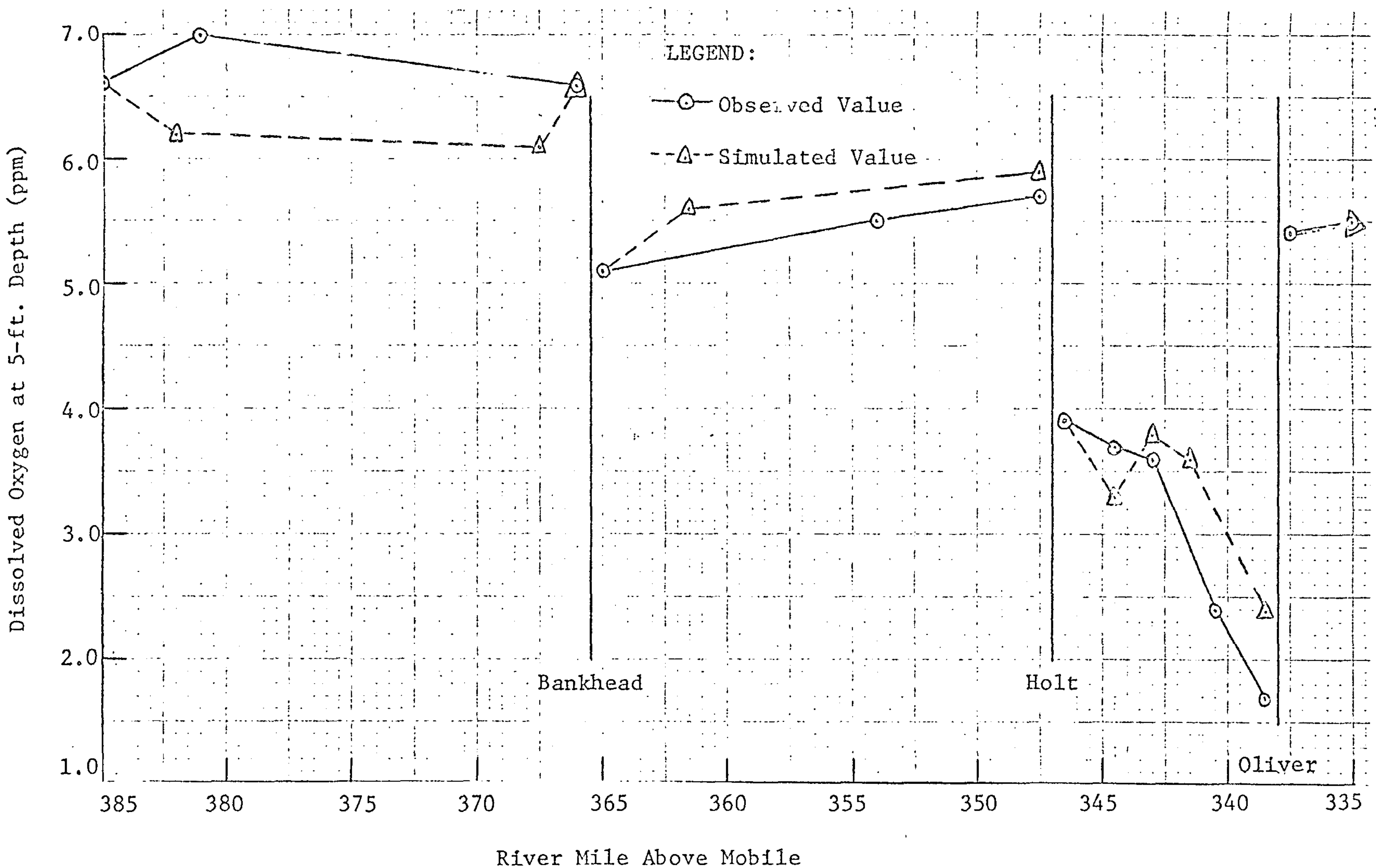


Figure 7. Dissolved Oxygen Profiles of Warrior River (August, 1972)

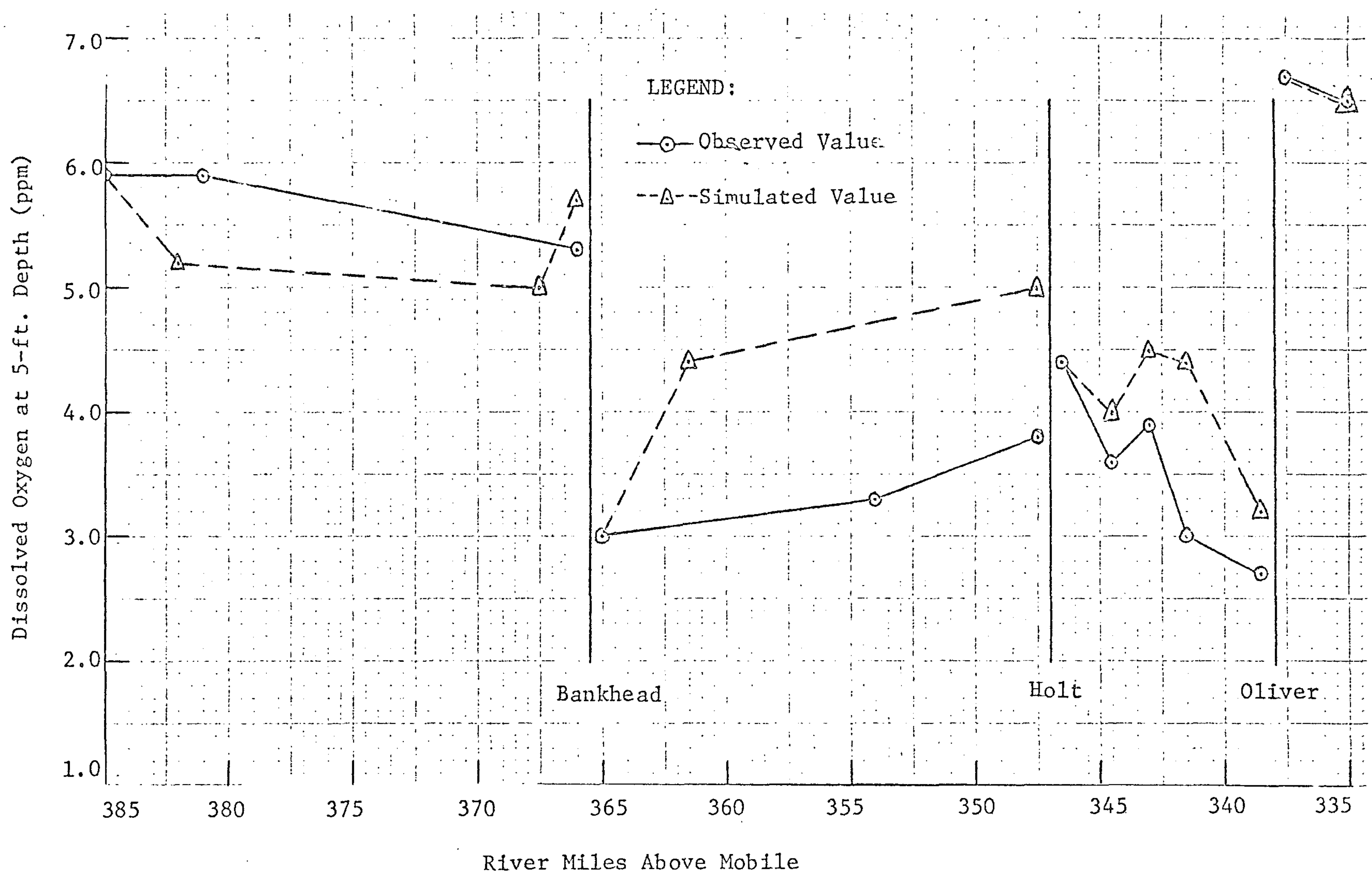


Figure 8. Dissolved Oxygen Profiles of Warrior River (September, 1972)

rather than representations of lateral or vertical profiles within the cross-section.

The lack of observed data at each point was such that the results of a rigorous statistical analysis would have been inconclusive. However, in view of the fact that observed values varied from the means at each point by as much as 10 percent and considering that in most cases the simulated values fall within plus or minus 10 percent of the observed values, the results of the simulation certainly seem to be adequate.

In those cases where the profiles differed by more than 10 percent, the discrepancy can be explained from a physical standpoint. In the Bankhead Pool the simulated profiles for each month exhibited the same general downward trend (proceeding downstream) shown by the observed profiles; however, the simulated values were somewhat lower than the corresponding observed values. This slight discrepancy is considered to be due to the complete mixing assumption employed in the DO prediction equation by Pyatt, Equation (9), which was applied in the highly-stratified Bankhead Pool. As a result, the simulated values represent more of an average of the higher observed values near the surface and the lower observed values at greater depths.

A sharp difference between simulated and observed profiles is noted in the Holt Pool near river mile 362. The observed profiles show an almost linear increase in DO between Bankhead Lock and Dam and Holt Lock and Dam, while the simulated profiles exhibit a much sharper increase in DO immediately below the Bankhead Lock and Dam. This is followed by a more moderate increase in DO from river mile 362 to the Holt Lock and Dam. The difference between the two profiles is probably due to the manner in which the profiles were drawn, that is, by connecting both the measured and calculated DO values on these profiles by straight line segments in which the dissolved oxygen values between separated points is not elucidated. The higher simulated dissolved oxygen value near river mile 362 is what one would intuitively expect as a result of the oxygen-depleted waters released from Bankhead Dam undergoing a much more rapid dissolved oxygen recovery than that shown in the observed profile due to the large oxygen deficit at this point and the corresponding high rate of reaeration.

In Oliver Pool the two profiles match quite well, with the simulated values slightly higher in most places. The above situation may be attributed to the use of the Streeter-Phelps equation for free-flowing conditions, Equation (7), which would be expected to yield moderately higher values of DO in a semi-impounded reservoir such as Oliver Pool.

Excellent results were obtained in that portion of the Warrior Pool studied, where the simulated and observed values agreed quite well.

In general, the model seems to work quite satisfactorily in predicting the dissolved oxygen profile of the Warrior River and it is anticipated that both this modeling technique and the supplementary computer program also developed in this study could be successfully applied to any river basin.

7.2 Selection of Locations Providing Optimum Water Quality Data

Since the primary purpose of the analysis performed in this study was to select those points which would provide the optimum water quality data with particular regard to the dissolved oxygen content, the simulated and observed DO profiles were utilized in accomplishing this objective. The selection of the following points for placement of the anticipated five DCPs was considered most advantageous from the standpoint of providing useful information:

(1) R. M. 385.0 (below the confluence of Locust and Mulberry Forks)--this point would provide data that could be used to evaluate the quality of water entering the section of the Warrior River considered in this investigation. Placement of a DCP here would provide for collection of data that is necessary as the initial input for the system into the developed model.

(2) R. M. 365.0 (one-half mile below Bankhead Dam)--monitoring at this location would give an indication of the quality of water entering the Holt Pool as well as monitoring the point of lowest dissolved oxygen content in that reservoir.

(3) R. M. 346.5 (one-half mile below Holt Dam)--Since Oliver Pool contains almost all the inputs from industries in the stretch of the river studied, a knowledge of the quality of the water entering this area would be of vital importance to effective management and control of this highly used water resource. Based on this reasoning, the placement of a DCP at this particular location would permit evaluation of the water quality before reaching the highly industrialized sector of the river further downstream in the Oliver Pool.

(4) R. M. 338.2 (forebay of Oliver Dam)--A DCP placed at this location would serve a two-fold purpose. First, it would

provide for monitoring of the point of lowest DO concentration in the Oliver Pool. Second, due to the general downward trend of the DO profile from Holt Dam to Oliver Dam, it would provide assurance that an improvement in water quality at this point would be indicative of improved quality in the entire reservoir.

(5) R. M. 335.0 (approximately three miles below Oliver Dam)--Monitoring performed at this location would provide data to be used for evaluation of the quality of water leaving the investigated area as well as for comparison with data collected at the entry point to the system for which the model was developed.

A map of the entire length of the river studied showing the selected DCP location sites is shown in Figure 9. Detailed maps of the river showing the segments used in modeling, the tributaries to the river, the locations of all significant waste discharges and the DCP locations are presented in Appendix III.

In addition to the reasons discussed above, these particular locations were selected to provide the initial input values of dissolved oxygen for each reservoir required in the developed mathematical model. Thus, values of dissolved oxygen (and other parameters) obtained from a relatively few critical locations may be utilized in the developed model to simulate and predict water quality over the entire reach of the river selected. As an example, values of dissolved oxygen measured by the DCP located just below Holt Lock and Dam (R. M. 346.5) may be used to predict DO values in the Oliver Pool as a function of the quantities and characteristics of the wastes discharged into this segment of the

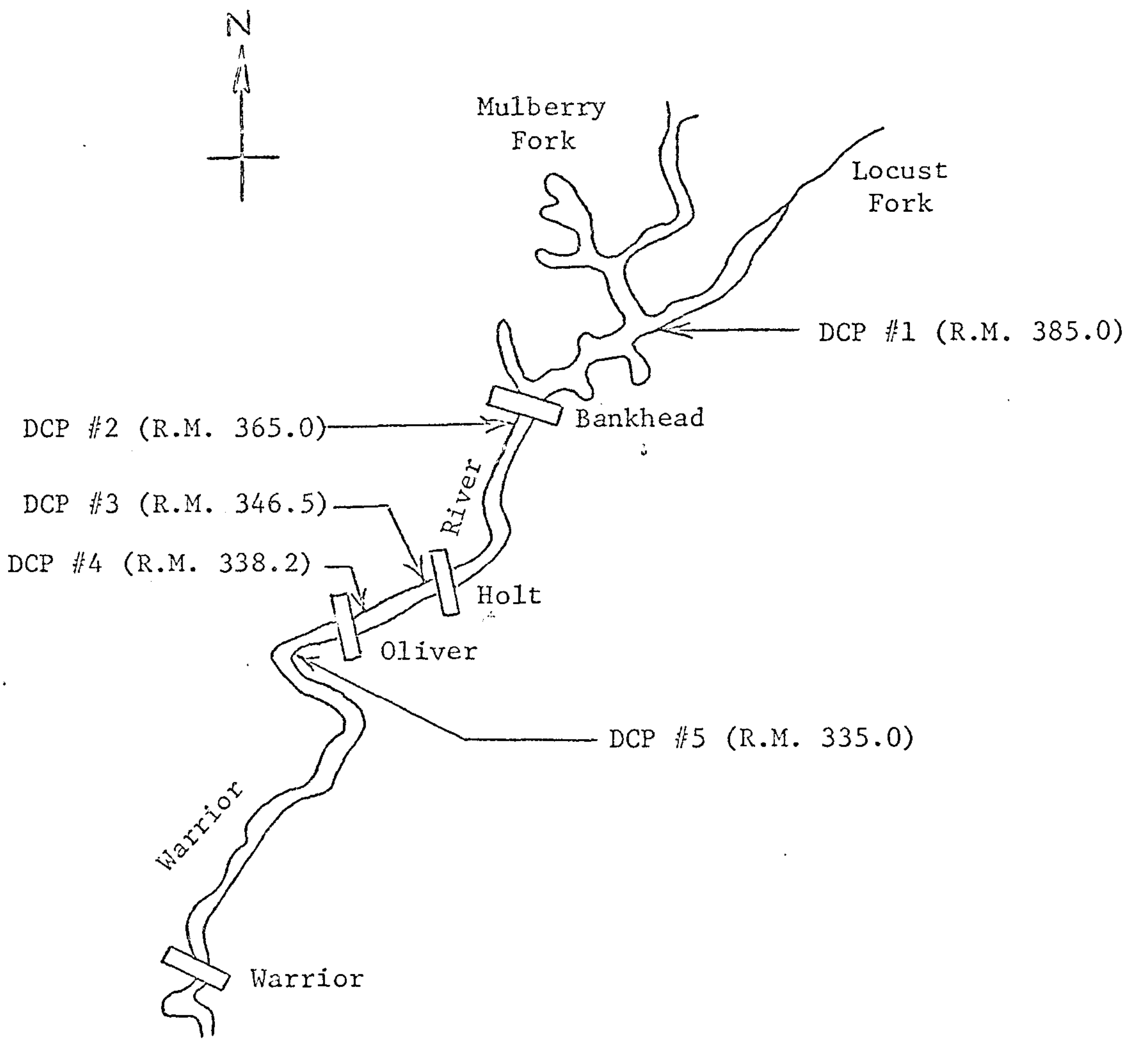


Figure 9. Locations of DCP Monitoring Sites

river. Alternately, the required DO level at this location may be obtained which will produce a desired water quality in the pool under varying loading conditions of discharged wastes. In this latter case, the information provided would assist in determining the amounts and characteristics of water to be released through the dam for a given set of waste inputs such that the desired water quality will be maintained. Additionally, the measured DO value and the resulting simulation model may be employed to predict the optimum point in time for discharge of impounded wastes by the industries in order that the water in the pool will not be degraded below the desired levels. Similar examples may be given for the simulation and management of water conditions in the Holt and Bankhead pools based upon the DO measurements at the DCP locations. Extension of the modeling technique over the entire reach of the river may be performed since water quality data in an upstream segment serves as input conditions to the successive downstream segments.

Although the model developed in this study was based primarily on dissolved oxygen, for the reasons previously given, it is in a form easily adaptable to simulating concentrations of dissolved constituents such as chlorides, sulfates, phosphates, and metals which might be present as a result of drainage from mining operations and runoff from agricultural activities. The net effect of many of these materials on the pH, conductivity, and temperature of the receiving water will be monitored by the DCPs and simulation of these effects may be obtained by use of portions of the developed model other than those applying to the DO prediction equations. For a detailed study of these types of constitutents, the DCPs may be moved to appropriate monitoring locations.

Although not investigated in this study, the use of DCP data in conjunction with ERTS imagery may be employed in a basin-wide study of the land use-water quality interaction. As indicated previously, the DCP will detect at its location the residual effect of upstream surface runoff and drainage from land-use activities.

In summary, the DCPs are intended to provide input data to the model developed for the river, enabling the model to be used as a valuable tool in formulating and implementing plans for the management of water resources and general environmental quality in a river basin.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The sites for placement of DCP monitors in the length of the Warrior River from the confluence of the Locust and Mulberry Forks to downstream of the Oliver Lock and Dam have been selected and proposed as desirable locations for the assessment of water quality. Dissolved oxygen was selected as the parameter of primary importance and the selection of the DCP sites was based on observed and predicted locations of critical dissolved oxygen concentrations.

To implement the selection process, a mathematical modeling technique and supplementary computer program were developed for simulating dissolved oxygen profiles. The modeling technique, based on modifications of the original Streeter-Phelps Equation by Pyatt, was shown to predict values of dissolved oxygen concentration in the Warrior River which either agreed quite well with the observed values or could be explained on the basis of actual river conditions. Based primarily on dissolved oxygen criteria, the following five locations were recommended for placement of the five DCPs designated for use in the Alabama ERTS project.

(1) R. M. 385.0--below the confluence of Locust and Mulberry Forks

(2) R. M. 365.0--one-half mile below Bankhead Lock and Dam

(3) R. M. 346.5--one-half mile below Holt Lock and Dam

(4) R. M. 338.2--forebay of Oliver Lock and Dam

(5) R. M. 335.0--approximately three miles below Oliver Lock and Dam.

In addition to monitoring dissolved oxygen, it is anticipated that the DCPs will serve to monitor the other parameters of pH, conductivity, and temperature to provide information concerning basin-wide land use activities. The portability feature of the DCP will allow selection of other monitoring points for more detailed information concerning specific parameters and their relationship to a variety of activities.

The selection of the specific monitoring sites in this study was designed to provide a basin-wide management capability in which the data obtained at a relatively few locations could be employed to simulate and predict water quality over an extensive river basin area. The selection methods proposed in this study were also developed for general applicability in the selection of desirable DCP or conventional monitoring sites in any water basin.

8.2. Recommendations

During the course of this investigation several possibilities for further study, primarily concerned with operation of the DCPs after installation, have become evident:

(1) Provide for the collection of supplementary dissolved oxygen data at locations where differences were obtained between simulated and observed values, permitting modification of the model to obtain better agreement with actual observed conditions.

(2) During the periods between overflights of the ERTS satellite, allow the DCP to operate as a conventional automated monitor, transmitting data to a ground receiving station.

(3) Include an addition to the DCP apparatus which would allow monitoring at different depths of the river, in order to evaluate the extent and effects of stratification in the reservoirs.

(4) Since the DCPs are portable, consider possible relocation of one or more of them in order to either expand or reduce the area of coverage, such as monitoring the quality of water in a clean stream (Mulberry Fork) in order to obtain base-line data on non-polluted conditions.

(5) Modify the DCP system for use as a network of conventional monitors after the ERTS satellite is removed from orbit.

APPENDICES

APPENDIX I

INFORMATION RELATED TO USE OF THE COMPUTER PROGRAM

A1.1 General

The actual computer programming utilized in the implementation of the simulation technique developed during this study was performed in the PL/1 programming language.[42] The IBM 360/50 computer installation at The University of Alabama was employed in running the program.

The following sections contain information directly related to the program that would be useful to those interested in the programming method and, in addition, examples are given of output for the Warrior River during the summer of 1972.

A1.2 Flow Diagram

Shown in Figure 10 is a diagram indicating the general path of logic followed by the model in simulating the dissolved oxygen profile in a stream. It is intended to show the general nature of the process rather than to show the specific calculations made by the program.

A1.3 Program Output

The output from the program is printed in a tabular form, with a separate table being used for the compilation of data predicted for each month. Examples of output containing simulated data for the area of the Warrior Basin during the months of June, 1972, through September, 1972, are shown in Tables VII through X.

A1.4 Definition of Variables

Summarized below are definitions for the variables used as input data to the program:

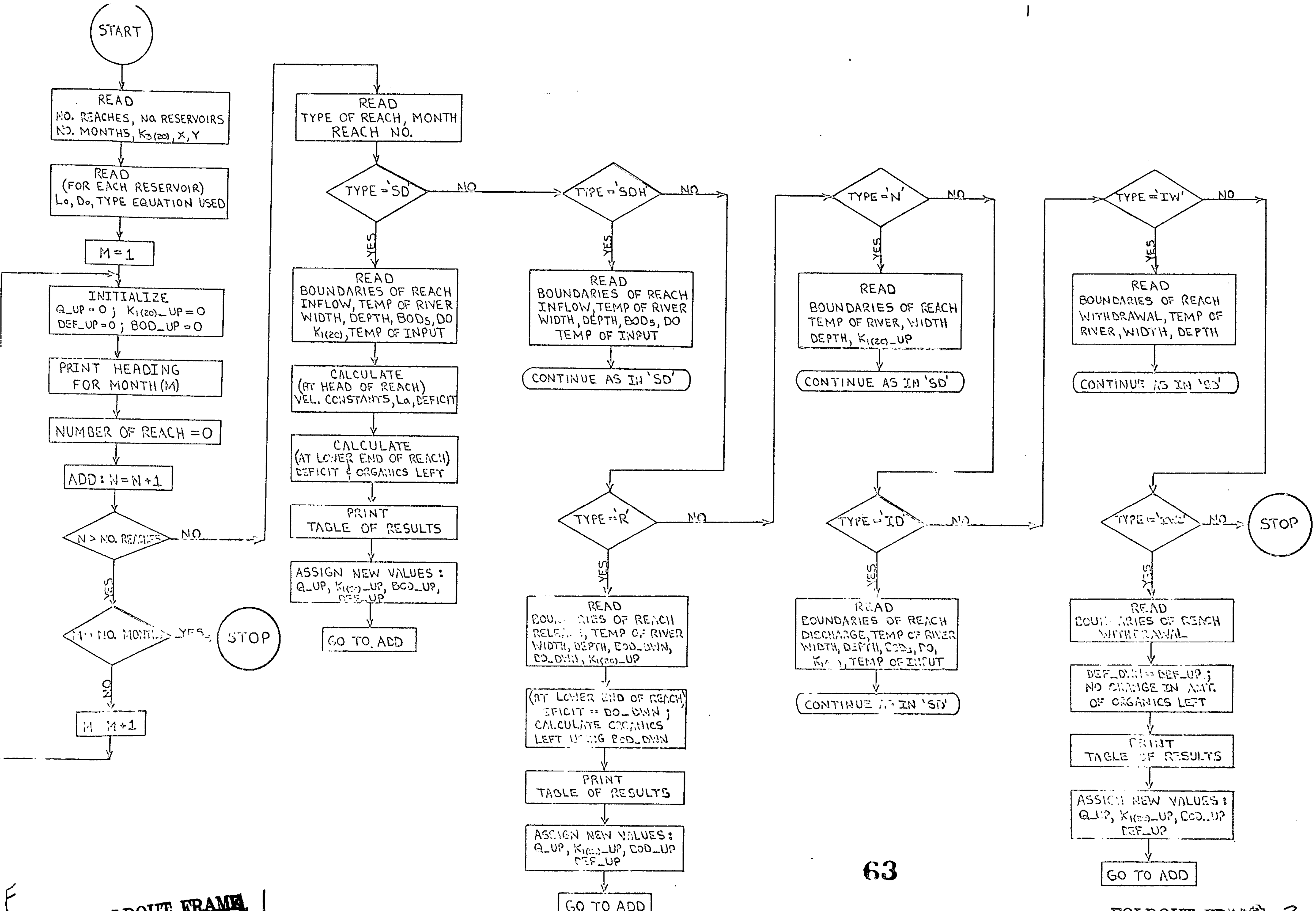

START
READ
NO. REACHES, NO. RESERVOIRS
NO. MONTHS, K3(20), X, Y
READ
(FOR EACH RESERVOIR)
Lo, Do, TYPE EQUATION USED
M = 1
INITIALIZE
Q_UP = 0 ; K1(20)_UP = 0
DEF_UP = 0 ; BOD_UP = 0
PRINT HEADING
FOR MONTH (M)
NUMBER OF REACH = 0
ADD: N = N + 1
N > NO. REACHES
NO
YES
M = NO. MONTHS
YES
STOP
NO
M = M + 1
READ
TYPE OF REACH, MONTH
REACH NO.
TYPE = 'SD'
NO
YES
READ
BOUNDARIES OF REACH
INFLOW, TEMP OF RIVER
WIDTH, DEPTH, BOD5, DO
K1(20), TEMP OF INPUT
CALCULATE
(AT HEAD OF REACH)
VEL. CONSTANTS, La, DEFICIT
CALCULATE
(AT LOWER END OF REACH)
DEFICIT & ORGANICS LEFT
PRINT
TABLE OF RESULTS
ASSIGN NEW VALUES:
Q_UP, K1(20)_UP, BOD_UP,
DEF_UP
GO TO ADD
TYPE = 'SDH'
NO
YES
READ
BOUNDARIES OF REACH
INFLOW, TEMP OF RIVER
WIDTH, DEPTH, BOD5, DO
TEMP OF INPUT
CONTINUE AS IN 'SD'
TYPE = 'R'
NO
YES
READ
BOUNDARIES OF REACH
RELEASE, TEMP OF RIVER
WIDTH, DEPTH, BOD_DWN,
DO_DWN, K1(20)_UP
(AT LOWER END OF REACH)
DEFICIT = DO_DWN ;
CALCULATE ORGANICS
LEFT USING BOD_DWN
PRINT
TABLE OF RESULTS
ASSIGN NEW VALUES:
Q_UP, K1(20)_UP, BOD_UP
DEF_UP
GO TO ADD
TYPE = 'N'
NO
YES
READ
BOUNDARIES OF REACH
TEMP OF RIVER, WIDTH
DEPTH, K1(20)_UP
CONTINUE AS IN 'SD'
TYPE = 'ID'
NO
YES
READ
BOUNDARIES OF REACH
DISCHARGE, TEMP OF RIVER
WIDTH, DEPTH, BOD5, DO,
K1(20), TEMP OF INPUT
CONTINUE AS IN 'SD'
TYPE = 'IW'
NO
YES
READ
BOUNDARIES OF REACH
WITHDRAWAL, TEMP OF
RIVER, WIDTH, DEPTH
CONTINUE AS IN 'SD'
TYPE = 'IWC'
NO
STOP
YES
READ
BOUNDARIES OF REACH
WITHDRAWAL
DEF_DWN = DEF_UP ;
NO CHANGE IN AMT.
OF ORGANICS LEFT
PRINT
TABLE OF RESULTS
ASSIGN NEW VALUES:
Q_UP, K1(20)_UP, BOD_UP
DEF_UP
GO TO ADD

TABLE VII

RESULTS OF SIMULATION OF WARRIOR RIVER (JUNE, 1972)

R. M. 385.0 TO R. M. 335.0

JUNE, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	1895.0		46153	4.58	0.190	0.014	6.0	5.6
2A	SD	382.00	367.50	1960.0		68294	44.30	0.196	0.006	5.6	5.0
3A	SDH	367.50	366.00	1970.0		78468	4.58	0.202	0.004	5.[illegible]	5.8
4A	R	366.00	365.40	1970.0	1970.0	92556	1.83	0.203	0.004	5.8	3.7
5A	N	365.40	361.50	1970.0		27787	3.40	0.176	0.046	3.7	5.1
6A	SDH	361.50	347.50	1985.0		56265	28.51	0.170	0.010	5.1	5.8
7A	R	347.50	346.90	1985.0	1880.0	86062	1.83	0.319	0.004	5.8	4.6
8A	N	346.90	346.30	1880.0		12294	0.24	0.193	0.178	4.6	4.5
9A	SD	346.30	345.70	1905.0		8587	0.16	0.192	0.137	4.5	4.6
10A	IWC	345.70	345.70	1904.3						4.6	4.6
10B	ID	345.70	345.20	1904.9		7761	0.12	0.198	0.180	4.6	4.6
10C	ID	345.20	344.40	1905.2		7761	0.20	0.196	0.180	4.6	4.5
11A	IWC	344.40	344.40	1903.4						4.5	4.5
11B	ID	344.40	344.39	1903.7		7191	0.00	0.195	0.180	4.5	4.5
11C	ID	344.39	343.70	1904.7		7191	0.16	0.195	0.180	4.5	4.5
12A	SDH	343.70	343.50	1974.7		7462	0.04	0.187	0.188	4.5	4.8
13A	ID	343.50	343.00	1980.1		7711	0.12	0.186	0.190	4.8	5.0
14A	IW	343.00	342.50	1952.2		9072	0.14	0.186	0.180	5.0	4.9
15A	ID	342.50	341.60	1970.7		7462	0.21	0.191	0.189	4.9	4.5
16A	SDH	341.60	338.41	1971.3		15443	1.62	0.190	0.053	4.5	3.4
17A	ID	338.41	338.39	1971.7		17589	0.01	0.187	0.030	3.4	3.4
18A	R	338.39	338.10	1971.7	2150.0	28912	0.29	0.125	0.020	3.4	6.6
19A	N	338.10	337.00	2150.0		9562	0.30	0.062	0.122	6.6	6.4
20A	IW	337.00	336.70	2149.3		7779	0.06	0.062	0.132	6.4	6.4
21A	ID	336.70	335.00	2150.0		6693	0.32	0.062	0.142	6.4	6.3

TABLE VIII

RESULTS OF SIMULATION OF WARRIOR RIVER (JULY, 1972)

R. M. 385.0 TO R. M. 335.0

JULY, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER E (PPM)
1A	SD	385.00	382.00	2150.0		46153	4.50	0.190	0.014	6.7	5.6
2A	SD	382.00	367.50	2250.0		68294	29.53	0.200	0.006	5.6	4.7
3A	SDH	367.50	366.00	2260.0		78468	4.58	0.197	0.004	4.7	5.4
4A	R	366.00	365.40	2260.0	2260.0	92556	1.83	0.194	0.004	5.4	3.4
5A	N	365.40	361.50	2260.0		27787	2.97	0.167	0.047	3.4	4.9
6A	SDH	361.50	347.50	2285.0		56265	21.38	0.163	0.012	4.9	5.7
7A	R	347.50	346.90	2285.0	2270.0	86062	1.83	0.307	0.004	5.7	4.3
8A	N	346.90	346.30	2270.0		12294	0.20	0.202	0.190	4.3	4.1
9A	SD	346.30	345.70	2305.0		8587	0.14	0.201	0.153	4.1	4.2
10A	INC	345.70	345.70	2304.3						4.2	4.2
10B	ID	345.70	345.20	2304.9		7761	0.10	0.205	0.200	4.2	4.0
10C	ID	345.20	344.40	2305.2		7761	0.16	0.204	0.200	4.0	3.7
11A	INC	344.40	344.40	2303.4						3.7	3.7
11B	ID	344.40	344.39	2303.7		7191	0.00	0.202	0.203	3.7	3.7
11C	ID	344.39	343.70	2304.9		7191	0.13	0.202	0.203	3.7	3.9
12A	SDH	343.70	343.50	2414.9		7462	0.03	0.199	0.213	3.9	4.1
13A	ID	343.50	343.00	2420.3		7711	0.09	0.197	0.218	4.1	4.2
14A	IW	343.00	342.50	2392.4		9072	0.11	0.197	0.208	4.2	4.2
15A	ID	342.50	341.60	2410.9		7462	0.17	0.194	0.211	4.2	4.1
16A	SDH	341.60	338.41	2411.3		15443	1.29	0.193	0.061	4.1	3.1
17A	ID	338.41	338.39	2412.0		17589	0.00	0.202	0.033	3.1	3.1
18A	R	338.39	338.10	2412.0	2630.0	28912	0.22	0.135	0.022	3.1	5.7
19A	N	338.10	337.00	2630.0		9562	0.24	0.067	0.139	5.7	5.7
20A	IW	337.00	336.70	2629.3		7779	0.05	0.067	0.152	5.7	5.7
21A	ID	336.70	335.00	2630.0		6693	0.26	0.067	0.162	5.7	5.7

TABLE IX

RESULTS OF SIMULATION OF WARRIOR RIVER (AUGUST, 1972)

R. M. 385.0 TO R. M. 335.0

AUGUST, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	1615.0		46153	6.11	0.218	0.012	6.6	6.2
2A	SD	382.00	367.50	1715.0		68294	44.30	0.218	0.007	6.2	6.1
3A	SDH	367.50	366.00	1730.0		78468	4.58	0.206	0.004	6.1	6.6
4A	R	356.00	365.40	1730.0	1730.0	92556	3.66	0.209	0.002	6.6	5.1
5A	N	365.40	361.50	1730.0		27787	3.97	0.183	0.044	5.1	5.6
6A	SDH	361.50	347.50	1740.0		56265	28.51	0.188	0.010	5.6	5.9
7A	R	347.50	346.90	1740.0	1730.0	86062	1.83	0.328	0.004	5.9	3.9
8A	N	346.90	346.30	1730.0		12294	0.26	0.207	0.177	3.9	3.6
9A	SD	346.30	345.70	1755.0		8587	0.18	0.206	0.133	3.6	3.6
10A	IWC	345.70	345.70	1754.3						3.6	3.6
10B	ID	345.70	345.20	1754.9		7761	0.13	0.210	0.176	3.6	3.5
10C	ID	345.20	344.40	1755.2		7761	0.22	0.208	0.176	3.5	3.3
11A	IWC	344.40	344.40	1753.4						3.3	3.3
11B	ID	344.40	344.39	1753.7		7191	0.00	0.207	0.176	3.3	3.3
11C	ID	344.39	343.70	1754.9		7191	0.17	0.207	0.176	3.3	3.2
12A	SDH	343.70	343.50	1864.9		7462	0.05	0.194	0.184	3.2	3.6
13A	ID	343.50	343.00	1870.3		7711	0.12	0.193	0.189	3.6	3.8
14A	IW	343.00	342.50	1842.4		9072	0.15	0.193	0.182	3.8	3.7
15A	ID	342.50	341.60	1860.9		7462	0.22	0.194	0.184	3.7	3.6
16A	SDH	341.60	338.41	1861.4		15443	1.62	0.193	0.054	3.6	2.4
17A	ID	338.41	338.39	1861.9		17589	0.01	0.193	0.028	2.4	2.4
18A	R	338.39	338.10	1861.9	2000.0	28912	0.29	0.131	0.020	2.4	5.4
19A	N	338.10	337.00	2000.0		9562	0.33	0.065	0.118	5.4	5.4
20A	IW	337.00	336.70	1999.3		7779	0.07	0.065	0.130	5.4	5.4
21A	ID	336.70	335.00	2000.0		6693	0.35	0.065	0.137	5.4	5.5

TABLE X

RESULTS OF SIMULATION OF WARRIOR RIVER (SEPTEMBER, 1972)

R. M. 385.0 TO R. M. 335.0

SEPTEMBER, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	1975.0		46153	4.58	0.199	0.014	5.9	5.2
2A	SD	382.00	367.50	2100.0		68294	29.53	0.203	0.006	5.2	5.0
3A	SDH	367.50	366.00	2110.0		78468	4.58	0.206	0.004	5.0	5.7
4A	R	366.00	365.40	2110.0	2110.0	92556	1.83	0.207	0.004	5.7	3.0
5A	N	365.40	361.50	2110.0		27787	3.40	0.180	0.046	3.0	4.4
6A	SDH	361.50	347.50	2125.0		56265	28.51	0.183	0.010	4.4	5.0
7A	R	347.50	346.90	2125.0	2040.0	86062	1.83	0.314	0.004	5.0	4.4
8A	N	346.90	346.30	2040.0		12294	0.22	0.207	0.190	4.4	4.2
9A	SD	346.30	345.70	2055.0		8587	0.15	0.206	0.143	4.2	4.2
10A	IWC	345.70	345.70	2054.3						4.2	4.2
10B	ID	345.70	345.20	2054.9		7761	0.11	0.204	0.190	4.2	4.1
10C	ID	345.20	344.40	2055.2		7761	0.18	[illegible]	0.190	4.1	4.0
11A	IWC	344.40	344.40	2053.4						4.0	4.0
11B	ID	344.40	344.39	2053.7		7191	0.00	0.201	0.190	4.0	4.0
11C	ID	344.39	343.70	2054.8		7191	0.15	0.201	0.190	4.0	4.0
12A	SDH	343.70	343.50	2194.8		7462	0.04	0.187	0.200	4.0	4.4
13A	ID	343.50	343.00	2200.2		7711	0.10	0.186	0.202	4.4	4.5
14A	IW	343.00	342.50	2172.3		9072	0.13	0.186	0.192	4.5	4.4
15A	ID	342.50	341.60	2190.8		7462	0.18	0.187	0.200	4.4	4.4
16A	SDH	341.60	338.41	2191.4		15443	1.39	0.186	0.058	4.4	3.2
17A	ID	338.41	338.39	2192.1		17589	0.01	0.186	0.030	3.2	3.2
18A	R	338.39	338.10	2192.1	2320.0	28912	0.25	0.128	0.022	3.2	6.7
19A	N	338.10	337.00	2320.0		9562	0.28	0.065	0.130	6.7	6.6
20A	IW	337.00	336.70	2319.3		7779	0.06	0.065	0.140	6.6	6.6
21A	ID	336.70	335.00	2320.0		6693	0.30	0.065	0.150	6.6	6.5

TOT_REACHES	total number of reaches into which the river is divided.
NOR	number of reservoirs on the stretch of the river being modeled.
NOM	number of months for which simulation is to be performed.
K320_E	deoxygenation constant due to bottom deposits at 20 °C. (base e), $days^{-1}$.
X	deoxygenation error term, $days^{-1}$.
Y	reaeration error term, $days^{-1}$.
LAI(S)	concentration of organic matter in reservoir S before waste inputs from upstream are added, mg/l.
DEFI(S)	concentration of dissolved oxygen in reservoir S before waste inputs from upstream are added, mg/l.
FORM(S)	type of equations used for predicting DO in reservoir S, Streeter-Phelps or modification by Pyatt for reservoirs.
TYPE	category of input for the reach in question--SD, SDH, R, N, ID, IW, IWC.
REACH	number of the reach.
MONTH	month for which the data was taken.
UPSTM	upstream boundary of the reach, river miles.
DWNSTM	downstream boundary of the reach, river miles.
DISCH	discharge of a tributary, cfs.
DIS_I	discharge of an industry, mgd.
WTHDR	amount of withdrawal by an industry, mgd.
REL	amount of flow released from a dam, cfs.
RIVTEMP	temperature of the river water, ^{o}C.
INTEMP	temperature of water in the input to a reach, ^{o}C.
WIDTH	surface width of the river, ft.
DEPTH	mean depth of the river in a reach, ft.

BOD5	BOD_5 of the input waste at 20 °C., mg/l.
BOD_DWN	BOD_5 of the river water (20 °C.) immediately below a dam, mg/l.
DO	dissolved oxygen concentration in the input to a reach, mg/l.
DO_DWN	dissolved oxygen concentration of the river water immediately below a dam, mg/l.
K120_10	deoxygenation constant at 20 °C. for the river water or input to a reach (base 10), days^{-1}.

A1.5 Listing of the Program Statements

On the following pages the actual PL/1 statements of the program are shown. It is hoped that any potential user employing the information provided in the preceding sections of Appendix I, in addition to these program statements, could either utilize the program intact or easily adapt the programming to fit his particular needs.

```
START: PROC OPTIONS(MAIN);
/**************************************************************************/
/**************************************************************************/
/** THIS PROGRAM SIMULATES DISSOLVED OXYGEN IN A RIVER ENVIRONMENT ***/
/**************************************************************************/
/**************************************************************************/
DCL ZILCH CHAR(1);
DCL (EXP1,EXP2) FIXED DECIMAL(5,3);
DCL FORM(4) CHAR(3) VARYING;
DCL CNT FIXED DECIMAL(3);
DCL CAPACITY(16) FIXED DECIMAL(5,0);
DCL (Q_IN(16),Q_OUT(16)) FIXED DECIMAL(6,1);
DCL (X,Y,WCHK) FIXED DECIMAL(5,3);
DCL (TYPE,REACH) CHAR(3) VARYING;
DCL (MO(4),MONTH) CHAR(9) VARYING;
DCL DATE(4) CHAR(15) VARYING;
DCL (TOT_REACHES,NOM,NOR,M,N,S,T) FIXED DECIMAL(2);
DCL (SLOPE,INTERCEPT) FIXED DECIMAL(6,4);
DCL (C,D,E,F,G,H,I,J,K,L,O,P,Q) FIXED DECIMAL(7,4);
DCL (BOD_UP,BOD5,LA_IN,LA,L_DWN,LA_INIT,BOD5_INIT,BOD_DWN,LA20,
   LAI(4)) FIXED DECIMAL(6,1);
DCL (RIVTEMP,INTEMP,DO,DO_UP,DO_DWN,DOSATR,DOSATW,DEF_UP,DEF_DWN,
   DEF_IN,DEF,DEF_INIT,DO_INIT,DEFI(4)) FIXED DECIMAL(4,1);
    DCL (K120_UP,K120_10,K120_E,K220_10,K220_E,K120_MIX,K1,K2,K3,
   K320_E,W,Z,A,B) FIXED DECIMAL(5,3);
DCL (Q_UP,DISCH,WIDTH,DEPTH,FLOW,REL) FIXED DECIMAL(6,1);
DCL (UPSTM,DWNSTM,DIS_I,WTHDR) FIXED DECIMAL(6,2);
DCL (LENGTH,CSA) FIXED DECIMAL(6);
DCL VEL FIXED DECIMAL(4,2);
DCL TIME FIXED DECIMAL(5,2);
DCL VOLUME FIXED DECIMAL(10);
MO(1)='JUNE';
MO(2)='JULY';
MO(3)='AUGUST';
MO(4)='SEPTEMBER';
GET EDIT(TOT_REACHES,NOR,NOM,K320_E,X,Y,ZILCH) (COL(1),F(2),COL(21),
   F(2),COL(31),F(2),COL(41),F(5,3),COL(51),F(5,3),COL(61),F(5,3),
   X(14),A(1));
DO S = 1 TO NOR;
GET EDIT(LAI(S),DEFI(S),FORM(S),ZILCH) (COL(1),F(5,1),COL(10),F(4,1),
   COL(20),A(3),X(57),A(1));
END;
M=1;
RESET: Q_UP = 0.0;
K120_UP=0.0;
DEF_UP=0.0;
BOD_UP=0.0;
PUT PAGE;
PUT SKIP(13) EDIT('SUMMARY FOR WARRIOR RIVER') (COL(48),A);
PUT SKIP(2) EDIT('R. M. 385.0  TO  R. M. 335.0') (COL(47),A);
DATE(M)=MO(M) || ', 1972';
PUT SKIP(2) EDIT(DATE(M)) (COL(54),A);
PUT SKIP(3) EDIT('REACH','TYPE','UPSTREAM','DOWNSTREAM','FLOW',
   'RELEASE','CSA','TRAVEL','K1','K2','DO','DO') (COL(1),A,COL(8),A,
   COL(15),A,COL(25),A,COL(38),A,COL(46),A,COL(59),A,COL(68),A,
```

```
   COL(80),A,COL(91),A,COL(102),A,COL(114),A);
PUT SKIP EDIT('NO.','R. M.','R. M.','(CFS)','(CFS)','(SQ. FT.)','TIME',
   '(BASE E)','(BASE E)','UPPER END','LOWER END') (COL(2),A,COL(17),A,
   COL(28),A,COL(38),A,COL(47),A,COL(56),A,COL(69),A,COL(77),A,
   COL(88),A,COL(99),A,COL(111),A);
PUT SKIP EDIT('(DAYS)','(PPM)','(PPM)') (COL(68),A,COL(101),A,
   COL(113),A);
PUT SKIP(2) EDIT(' ') (COL(2),A);
N = 0;
T = 0;
ADD: N=N+1;
IF N = 1 THEN DO;
T = T + 1;
LA_INIT = LAI(T);
DEF_INIT = DEFI(T);
END;
ELSE GO TO CHECK;
CHECK: IF N > TOT_REACHES THEN DO;
IF M=NOM THEN GO TO LAST;
ELSE GO TO NEXT;
NEXT: M=M+1;
GO TO RESET;  END;
ELSE DO;
READ: GET EDIT(TYPE,REACH,MONTH) (COL(1),A(3),COL(6),A(3),COL(11),
   A(9));  END;
/*************************************************************************/
/*************************************************************************/
/************** POLLUTED STREAM DISCHARGING INTO RIVER **************/
/*************************************************************************/
/*************************************************************************/
IF TYPE='SD' THEN DO;
STREAM:GET EDIT(UPSTM,DWNSTM,DISCH,RIVTEMP,WIDTH,DEPTH)(COL(25),F(6,2),
   COL(35),F(6,2),COL(45),F(6,1),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
GET EDIT(BOD5,DO,K120_10,INTEMP,ZILCH) (COL(25),F(6,1),COL(37),F(4,1),
   COL(46),F(5,3),COL(57),F(4,1),X(19),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR - DEF_UP;
DOSATW = 14.65 - 0.41*INTEMP + 0.008*INTEMP**2 - 0.00008*INTEMP**3;
LENGTH = (UPSTM - DWNSTM) * 5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW = Q_UP + DISCH;
VEL = FLOW/CSA;
TIME = (LENGTH/VEL) / 86400.0;
K120_E = K120_10 * 2.303;
K120_MIX = ((K120_UP*Q_UP) + (K120_E*DISCH)) / FLOW;
K220_10 = (12.90 * VEL**0.5) / (DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1 = K120_MIX * 1.047**(RIVTEMP-20.0);
K2 = K220_F * 1.0159**(RIVTEMP-20.0);
K3 = K320_F * 1.047**(RIVTEMP-20.0);
LA_IN = BOD5 / (1.0-1.0/(2.71**(5*K120_E)));
LA20 = ((BOD_UP * Q_UP) + (LA_IN * DISCH))/FLOW;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
```

```
DEF_IN = DOSATU - DO;
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF = (((DOSATR-DO_UP) * Q_UP) + (DEF_IN * DISCH)) / FLOW;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
IF N=1 THEN Z = DISCH * (86400.0/VOLUME);
ELSE Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_SD:  L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_SD:  DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_SD: PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN) (COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),
   F(6,2),COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),
   COL(90),F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP = FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP = K120_MIX;
GO TO ADD;
END;
/*****************************************************************/
/*****************************************************************/
/*************** CLEAN STREAM DISCHARGING INTO RIVER ***************/
/*****************************************************************/
/*****************************************************************/
ELSE IF TYPE = 'SDH' THEN DO;
STREAM_CLEAN: GET EDIT(UPSTM,DWNSTM,DISCH,RIVTEMP,WIDTH,DEPTH)
   (COL(25),F(6,2),COL(35),F(6,2),COL(45),F(6,1),COL(57),F(4,1),
```

```
   COL(65),F(6,1),COL(75),F(6,1));
GET EDIT(DO,INTEMP,ZILCH)(COL(37),F(4,1),COL(57),F(4,1),X(19),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP = DOSATR - DEF_UP;
DOSATW = 14.65 - 0.41*INTEMP + 0.008*INTEMP**2 - 0.00008*RIVTEMP**3;
LENGTH = (UPSTM - DWNSTM) * 5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW = Q_UP + DISCH;
VEL = FLOW / CSA;
TIME = (LENGTH/VEL) / 86400.0;
K120_MIX = (K120_UP * Q_UP) / FLOW;
K220_10 = (12.90 * VEL**0.5) / (DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1 = K120_MIX * 1.047**(RIVTEMP-20.0);
K2 = K220_E * 1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = (BOD_UP * Q_UP) / FLOW;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DEF_IN = DOSATW - DO;
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF = (((DOSATR - DO_UP) * Q_UP) + (DEF_IN * DISCH)) / FLOW;
IF FORM(I) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
IF N=1 THEN Z = DISCH * (86400.0/VOLUME);
ELSE Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_SDH: L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_SDH: DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
```

```
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_SDH: PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN) (COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),
   F(6,2),COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),
   COL(90),F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP = FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP = K120_MIX;
GO TO ADD;
END;
/**************************************************************************/
/**************************************************************************/
/**** REACH CONTAINING A DAM OR OTHER FLOW CONTROLLING STRUCTURE ****/
/**************************************************************************/
/**************************************************************************/
ELSE IF TYPE= 'R' THEN DO;
RESERVOIR: GET EDIT(UPSTM,DWNSTM,REL,RIVTEMP,WIDTH,DEPTH) (COL(25),
   F(6,2),COL(35),F(6,2),COL(45),F(6,1),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
GET EDIT(BOD_DWN,DO_DWN,K120_20,ZILCH) (COL(25),F(6,1),COL(37),F(4,1),
   COL(56),F(5,3),X(19),A(1));
IF N=1 THEN DO_UP = DO;
ELSE DO_UP = DOSATR - DEF_UP;
LENGTH = (UPSTM - DWNSTM) * 5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW = Q_UP;
VEL = FLOW / CSA;
TIME = (LENGTH/VEL) / 86400.0;
K120_E = K120_20 * 2.303;
K120_MIX = K120_E;
K220_20 = (12.90 * VEL**0.5) / (DEPTH**1.5);
K220_E = K220_20 * 2.303;
K1 = K120_MIX * 1.047**(RIVTEMP-20.0);
K2 = K220_E * 1.0159**(RIVTEMP-20.0);
K3 = K320_F * 1.047**(RIVTEMP-20.0);
LA20 = BOD_UP;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF = DOSATR - DO_UP;
DEF_DWN = DOSATR - DO_DWN;
PRINT_R:PUT SKIP EDIT (REACH, TYPE, UPSTM, DWNSTM, FLOW, REL, CSA, TIME
   , K1, K2, DO_UP, DO_DWN) (COL(2),A(3), COL(9), A(3), COL(17), F(6,2)
   , COL(28), F(6,2), COL(37), F(6,1), COL(47), F(6,1), COL(58), F(6),
   COL(68), F(5,2), COL(79), F(5,3), COL(90), F(5,3),COL(101), F(4,1),
   COL(113),F(4,1));
Q_UP=REL;
DEF_UP=DEF_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/**************************************************************************/
/**************************************************************************/
/*************** REACH CONTAINING NO INPUT TO RIVER ****************/
```

```
/*************** OCCURS BELOW REACH CONTAINING A DAM ***************/
/*******************************************************************/
/*******************************************************************/
ELSE IF TYPE = 'N' THEN DO;
T = T + 1;
LA_INIT = LA(T);
DEF_INIT = DEF(T);
NO_INPUT: GET EDIT (UPSTM, DWNSTM, DISCH, RIVTEMP, WIDTH, DEPTH) (COL(
   25), F(6,2), COL(35), F(6,2), COL(45), F(6,1), COL(57), F(4,1), COL(
   65), F(6,1), COL(75), F(6,1));
GET EDIT(K120_10,ZILCH)(COL(26), F(5,3),X(49),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
LENGTH=(UPSTM-DWNSTM)*5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW=Q_UP+DISCH;
VEL=FLOW/CSA;
TIME=(LENGTH/VEL)/86400.0;
K120_E=K120_10*2.303;
K120_MIX=K120_E;
K220_10=(12.90*VEL**0.5)/(DEPTH**1.5);
K220_E=K220_10*2.303;
K1=K120_MIX*1.047**(RIVTEMP-20.0);
K2=K220_E*1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = BOD_DWN / (1.0-1.0/(2.71**(5*K120_E)));
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF=DOSATR-DO_UP;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_N:    L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_N:    DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
```

```
P = (X+Y)/K1;
DEF_DWN = (L*D + DEF + P) * EXP1 - P;    END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));    END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_N:PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,DO_UP
   ,DO_DWN)(COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),
   COL(37),F(6,1),COL(50),F(6),COL(68),F(5,2),COL(79),F(5,3),COL(90),
   F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/*****************************************************************************/
/*****************************************************************************/
/*************** INDUSTRY DISCHARGING WASTE INTO RIVER **************/
/*****************************************************************************/
/*****************************************************************************/
ELSE IF TYPE='ID' THEN DO;
IND_DIS:GET EDIT(UPSTM,DWNSTM,DIS_I,RIVTEMP,WIDTH,DEPTH)(COL(25),F(6,2)
   ,COL(35),F(6,2),COL(45),F(6,2),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
GET EDIT(BOD5,DO,K120_IO,INTEMP,ZILCH)(COL(25),F(6,1),COL(37),F(4,1),
   COL(46),F(5,3), COL(57),F(4,1),X(19),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
DOSATW = 14.65 - 0.41*INTEMP + 0.008*INTEMP**2 - 0.00008*INTEMP**3;
LENGTH=(UPSTM-DWNSTM)*5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW=Q_UP+(DIS_I*1.545);
VEL=FLOW/CSA;
TIME=(LENGTH/VEL)/86400.0;
K120_E=K120_IO*2.303;
K120_MIX=((K120_UP*Q_UP)+(K120_E*(DIS_I*1.545)))/FLOW;
K220_IO=(12.90*VEL**0.5)/(DEPTH**1.5);
K220_E=K220_IO*2.303;
K1=K120_MIX*1.047**(RIVTEMP-20.0);
K2=K220_E*1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA_IN=BOD5/(1.0-1.0/(2.71**(5*K120_E)));
LA20 = ((BOD_UP*Q_UP) + (LA_IN * DIS_I)) / FLOW;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DEF_IN=DOSATW-DO;
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF=(((DOSATR-DO_UP)*Q_UP)+(DEF_IN*DIS_I))/FLOW;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
```

G

```
B = K2 + W;
BOD_ID:  L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_ID:  DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_ID:PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN)(COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),
   COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),COL(90),
   F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/*************************************************************************/
/*************************************************************************/
/*************** INDUSTRY WITHDRAWING WATER FROM RIVER ***************/
/*************************************************************************/
/*************************************************************************/
ELSE IF TYPE='IW' THEN DO;
IND_WTHDRWL:GET EDIT(UPSTM,DWNSTM,WTHDR,RIVTEMP,WIDTH,DEPTH)(COL(25),
   F(6,2),COL(35),F(6,2),COL(45),F(6,2),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
LENGTH=(UPSTM-DWNSTM)*5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW=Q_UP+(WTHDR*1.545);
VEL=FLOW/CSA;
```

```
TIME=(LENGTH/VEL)/86400.0;
K120_MIX=K120_UP;
K220_10=(12.90*VEL**0.5)/(DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1=K120_MIX*1.047**(RIVTEMP-20.0);
K2=K220_E*1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = BOD_UP * (FLOW/Q_UP);
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF=DOSATR-DO_UP;
IF FORM(IT) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_IN:  L_DWN = LA_INIT    )/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_IN:  DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_IN:PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN)(COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),
   COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),COL(90),
   F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/*****************************************************************/
```

```
/*************************************************************************/
/*************** INDUSTRY WITHDRAWING WATER FROM RIVER **************/
/** REACH IN WHICH AN INDUSTRY'S WITHDRAWAL AND DISCHARGE POINTS ****/
/********* ARE CLOSE ENOUGH TO BE CONSIDERED AS ONE POINT ***********/
/*************************************************************************/
/*************************************************************************/
ELSE IF TYPE='IWC' THEN DO;
IND_WTHDRW_CON: GET EDIT(UPSTM,DWNSTM,WTHDR,ZILCH)(COL(25),F(6,2),
   COL(35),F(6,2),COL(45),F(6,2),X(29),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
FLOW=Q_UP+(WTHDR*1.545);
DO_DWN=DO_UP;
LA20 = BOD_UP * (FLOW/Q_UP);
PRINT_IWC: PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,DO_UP,DO_DWN)
   (COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),COL(37),
   F(6,1),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = LA20;
DEF_UP=DEF_DWN;
K120_UP=K120_MIX;
GO TO ADD;
LAST:END START;
```

APPENDIX II

DATA FOR EACH REACH

FOR

JUNE 1972--SEPTEMBER 1972

TABLE XI

CLASSIFICATION, RIVER MILE LOCATION, AND CHANNEL DIMENSIONS OF WARRIOR RIVER REACHES

Reach No.	Classi-fication	Upstream River Mile	Downstream River Mile	Average Width (ft.)	Average Depth (ft.)
1A	SD	385.00	382.00	1125	54.7
2A	SD	382.00	367.50	1270	71.7
3A	SDH	367.50	366.00	1250	83.7
4A	R	366.00	365.00	1440	85.7
5A	N	365.40	361.50	1140	32.5
6A	SDH	361.50	347.50	1240	60.5
7A	R	347.50	346.90	1500	76.5
8A	N	346.90	346.30	970	16.9
9A	SD	346.30	345.70	500	22.9
10A	IWC	345.70	345.70	--	- -
10B	ID	345.70	345.20	520	19.9
10C	SDH	345.20	344.40	520	19.9
11A	IWC	344.40	344.40	--	- -
11B	ID	344.40	344.39	470	20.4
11C	ID	344.39	343.70	470	20.4
12A	SDH	343.70	343.50	500	19.9
13A	ID	343.50	343.00	530	19.4
14A	IW	343.00	342.50	640	18.9
15A	ID	342.50	341.60	500	19.9
16A	SDH	341.60	338.41	590	34.9
17A	ID	338.41	338.39	470	49.9
18A	R	338.39	338.10	750	51.4
19A	N	338.10	337.00	510	25.0
20A	IW	337.00	336.70	410	25.3
21A	ID	336.70	335.00	350	25.5

TABLE XII

INPUT DATA FOR WARRIOR RIVER REACHES

Reach No.	Month	Input Flow (cfs)	River Temperature (^{o}C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 ^{o}C Input (base 10) (days^{-1})	Temperature Input (^{o}C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 ^{o}C of River (base 10) (days^{-1})
1A	June	1895.0	27.0	2.5	6.0	0.060	27.0			
	July	2150.0	27.9	3.2	6.7	0.060	27.9			
	August	1615.0	30.0	1.0	6.6	0.060	30.0			
	September	1975.0	28.0	3.0	5.9	0.060	28.0			
2A	June	65.0	27.7	2.5	7.0	0.060	25.6			
	July	100.0	29.0	3.5	5.2	0.060	28.9			
	August	100.0	30.0	3.5	7.1	0.060	28.9			
	September	125.0	28.5	2.5	6.5	0.060	25.0			
3A	June	10.0	28.5		8.0		20.0			
	July	10.0	28.0		8.0		22.2			
	August	15.0	29.1		8.0		22.8			
	September	10.0	28.9		8.0		22.8			
4A	June	1970.0	28.5					1.0	3.7	0.060
	July	2260.0	27.5					1.5	3.4	0.060
	August	1730.0	29.1					1.5	5.1	0.060
	September	2110.0	28.9					1.5	3.0	0.060

TABLE XII (Continued)

Reach No.	Month	Input Flow (cfs)	River Temperature (°C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 °C Input (base 10) ($days^{-1}$)	Temperature Input (°C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 °C of River (base 10) ($days^{-1}$)
5A	June	0.0	27.3							0.055
	July	0.0	26.2							0.055
	August	0.0	28.2							0.055
	September	0.0	27.8							0.055
6A	June	15.0	26.7		5.0		22.2			
	July	25.0	26.0		5.0		23.3			
	August	10.0	29.0		4.6		26.7			
	September	15.0	28.3		4.8		26.7			
7A	June	1880.0	28.3					2.7	4.6	0.095
	July	2270.0	27.5					3.5	4.3	0.095
	August	1730.0	28.9					4.0	3.9	0.095
	September	2040.0	28.0					4.0	4.4	0.095
8A	June	0.0	25.7							0.065
	July	0.0	26.7							0.065
	August	0.0	27.2							0.065
	September	0.0	27.2							0.065
9A	June	25.0	25.7	2.0	8.0	0.060	25.6			
	July	35.0	26.7	2.5	8.0	0.060	28.9			
	August	25.0	27.2	2.5	8.0	0.060	28.9			
	September	15.0	27.2	2.6	9.4	0.060	25.6			

TABLE XII (Continued)

Reach No.	Month	Input Flow (cfs)	River Temperature (^oC)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 ^oC Input (base 10) ($days^{-1}$)	Temperature Input (^oC)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 ^oC of River (base 10) ($days^{-1}$)
10A	June	- 0.43								
	July	- 0.43								
	August	- 0.43								
	September	- 0.43								
10B	June	0.40	26.5	610.0	0.0	0.005	33.0			
	July	0.43	27.3	450.0	0.0	0.005	33.0			
	August	0.43	27.8	280.0	0.0	0.005	33.0			
	September	0.42	27.2	410.0	0.0	0.005	33.0			
10C	June	0.20	26.5	1550.0	0.0	0.025	33.0			
	July	0.20	27.3	1550.0	0.0	0.025	33.0			
	August	0.20	27.8	1550.0	0.0	0.025	33.0			
	September	0.20	27.2	1550.0	0.0	0.025	33.0			
11A	June	- 1.12								
	July	- 1.12								
	August	- 1.12								
	September	- 1.12								
11B	June	0.21	26.5	5.0	3.0	0.025	34.4			
	July	0.21	27.3	5.0	3.0	0.025	34.4			
	August	0.21	27.8	5.0	3.0	0.025	34.4			
	September	0.21	27.2	5.0	3.0	0.025	34.4			

TABLE XII (Continued)

Reach No.	Month	Input Flow (cfs)	River Temperature (°C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 °C Input (base 10) ($days^{-1}$)	Temperature Input (°C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 °C of River (base 10) ($days^{-1}$)
11C	June	0.70	26.5	84.0	0.0	0.085	33.0			
	July	0.80	27.3	52.0	0.0	0.085	33.0			
	August	0.78	27.8	54.0	0.0	0.085	34.0			
	September	0.72	27.2	46.0	0.4	0.085	33.0			
12A	June	70.0	26.5		7.5		25.0			
	July	110.0	28.0		7.0		28.9			
	August	110.0	27.8		7.0		27.8			
	September	140.0	27.2		7.5		24.4			
13A	June	3.50	26.5	2.2	5.0	0.002	24.0			
	July	3.50	28.0	2.2	5.0	0.002	24.0			
	August	3.50	27.8	2.2	5.0	0.002	24.0			
	September	3.50	27.2	2.2	5.0	0.002	24.0			
14A	June	- 18.00	26.5							
	July	- 18.00	28.0							
	August	- 18.00	27.8							
	September	- 18.00	27.2							
15A	June	12.00	27.0	100.0	0.0	0.135	35.0			
	July	12.00	27.5	100.0	0.0	0.135	35.0			
	August	12.00	27.8	100.0	0.0	0.135	35.0			
	September	12.00	27.2	100.0	0.0	0.135	35.0			

TABLE XII (Continued)

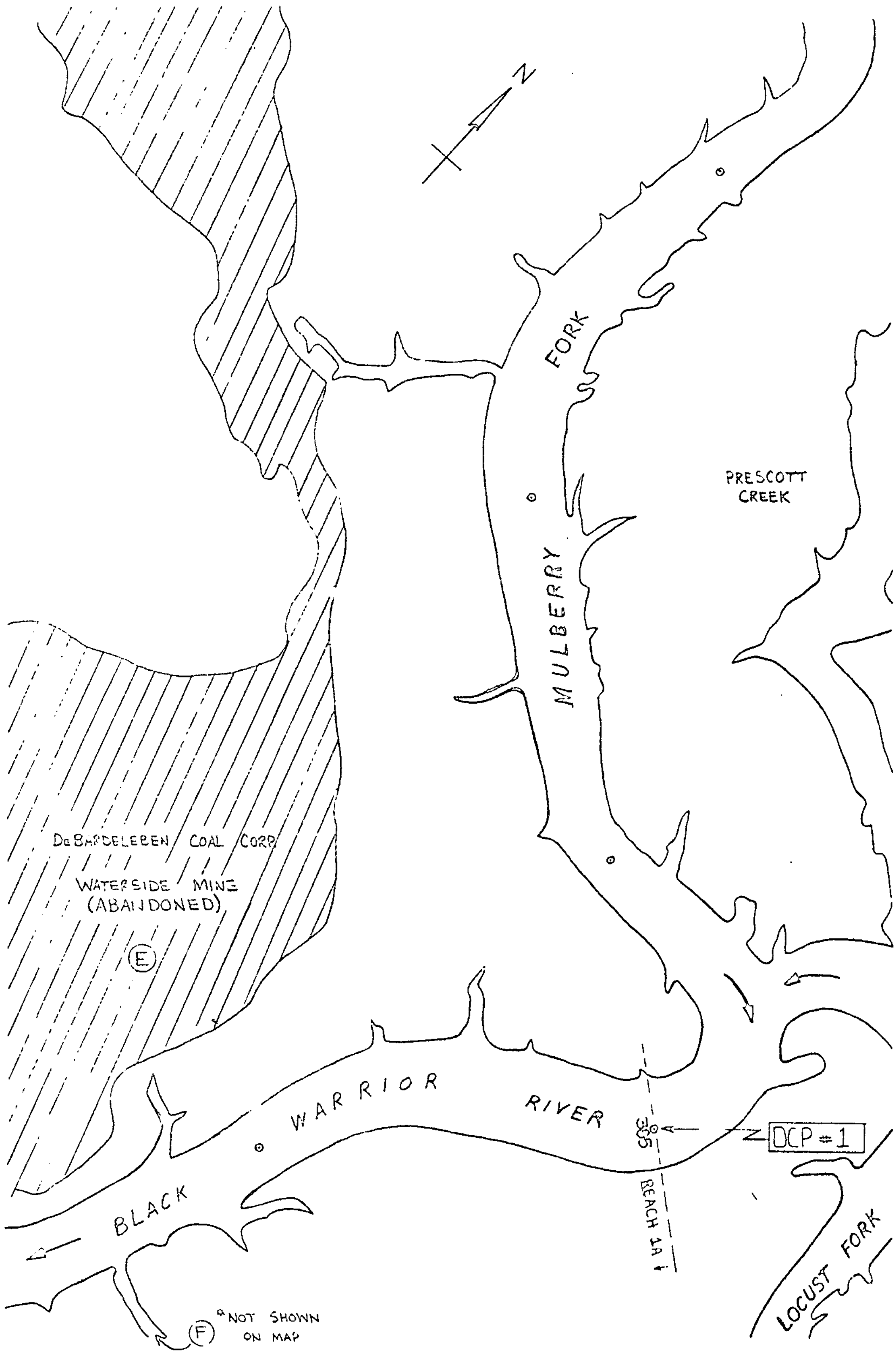
Reach No.	Month	Input Flow (cfs)	River Tempera-ture (^oC)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 ^oC Input (base 10) ($days^{-1}$)	Tempera-ture Input (^oC)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 ^oC of River (base 10) ($days^{-1}$)
16A	June	0.6	27.0		4.0		21.0			
	July	0.4	27.5		4.0		23.0			
	August	0.5	27.8		4.0		22.0			
	September	0.6	27.2		4.0		21.0			
17A	June	0.32	26.7	58.0	7.0	0.100	27.0			
	July	0.50	28.5	40.0	8.0	0.100	28.0			
	August	0.38	27.8	28.0	9.0	0.100	28.0			
	September	0.50	27.2	60.0	7.0	0.100	27.0			
18A	June	2150.0	26.7					2.5	6.6	0.040
	July	2630.0	28.5					1.5	5.7	0.040
	August	2000.0	27.8					1.0	5.4	0.040
	September	2320.0	27.2					2.0	6.7	0.040
19A	June	0.0	26.7							0.020
	July	0.0	28.5							0.020
	August	0.0	27.8							0.020
	September	0.0	27.8							0.020
20A	June	- 0.40	26.7							
	July	- 0.40	28.5							
	August	- 0.40	27.8							
	September	- 0.40	27.8							

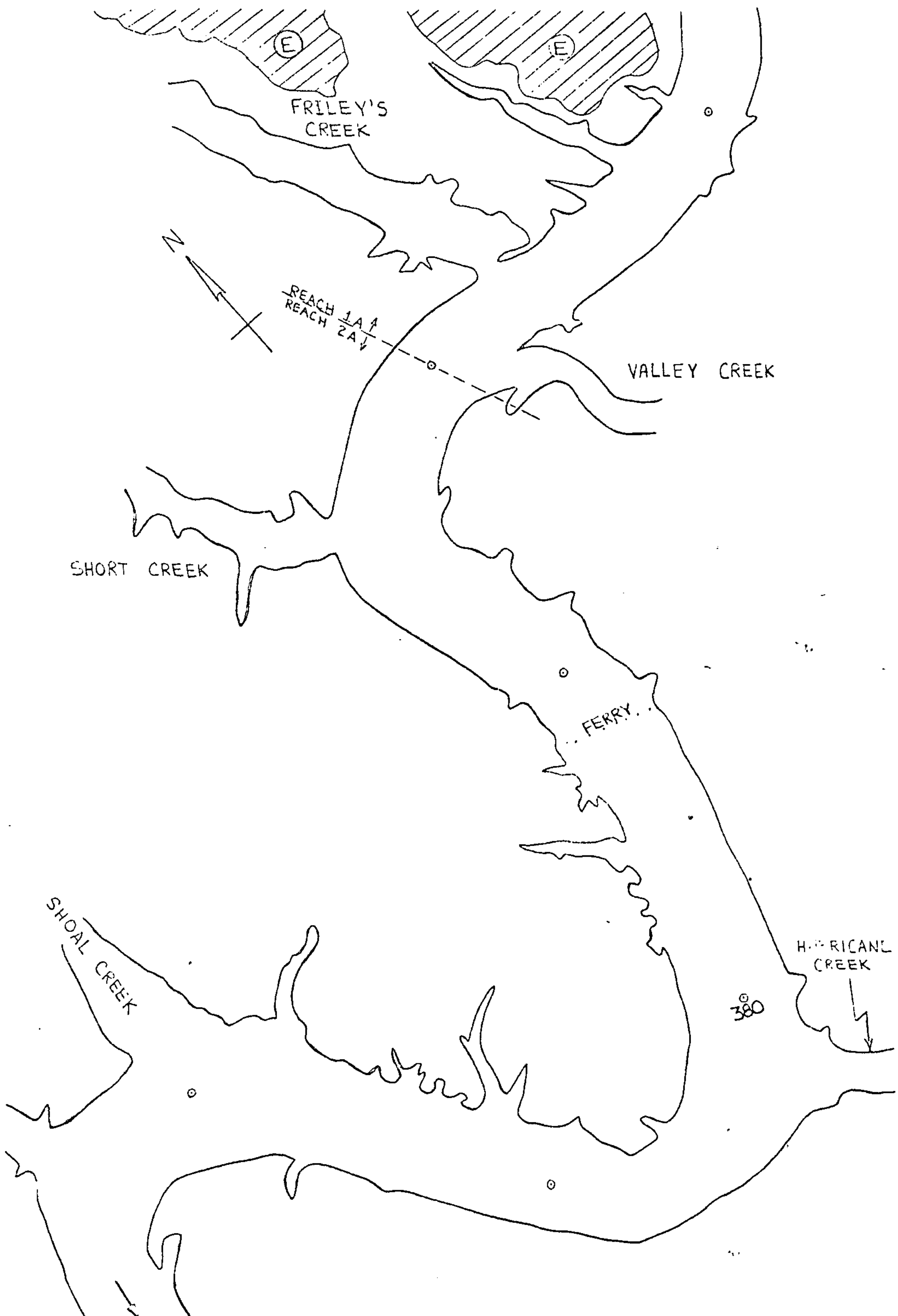
TABLE XII (Continued)

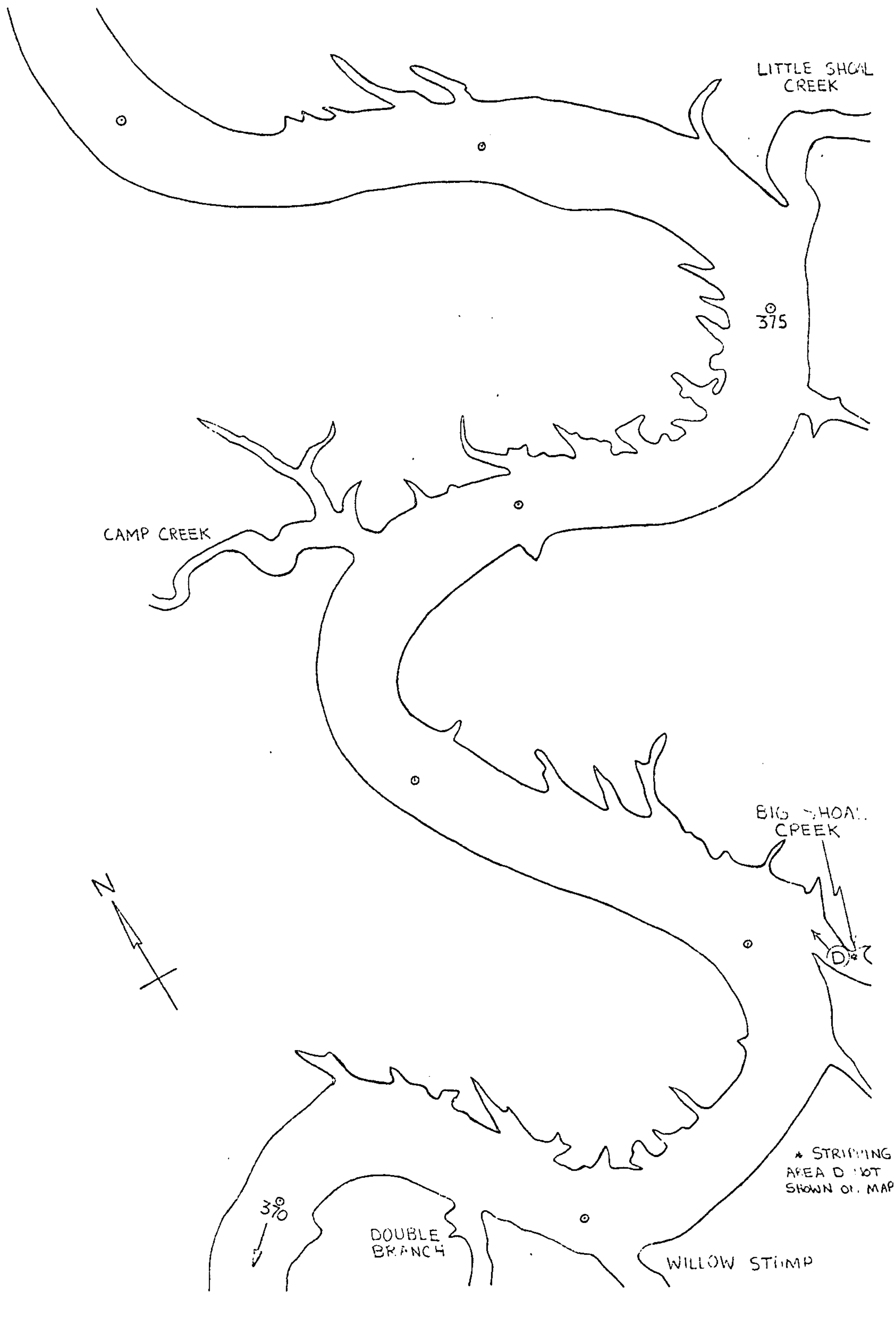
Reach No.	Month	Input Flow (cfs)	River Temperature (^{o}C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 ^{o}C Input (base 10) (days^{-1})	Temperature Input (^{o}C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 ^{o}C of River (base 10) (days^{-1})
21A	June	0.46	26.7	22.0	2.9	0.025	35.0			
	July	0.46	28.5	22.0	2.9	0.025	35.0			
	August	0.46	27.8	27.0	3.0	0.025	35.0			
	September	0.46	27.8	27.0	3.0	0.025	35.0			

APPENDIX III

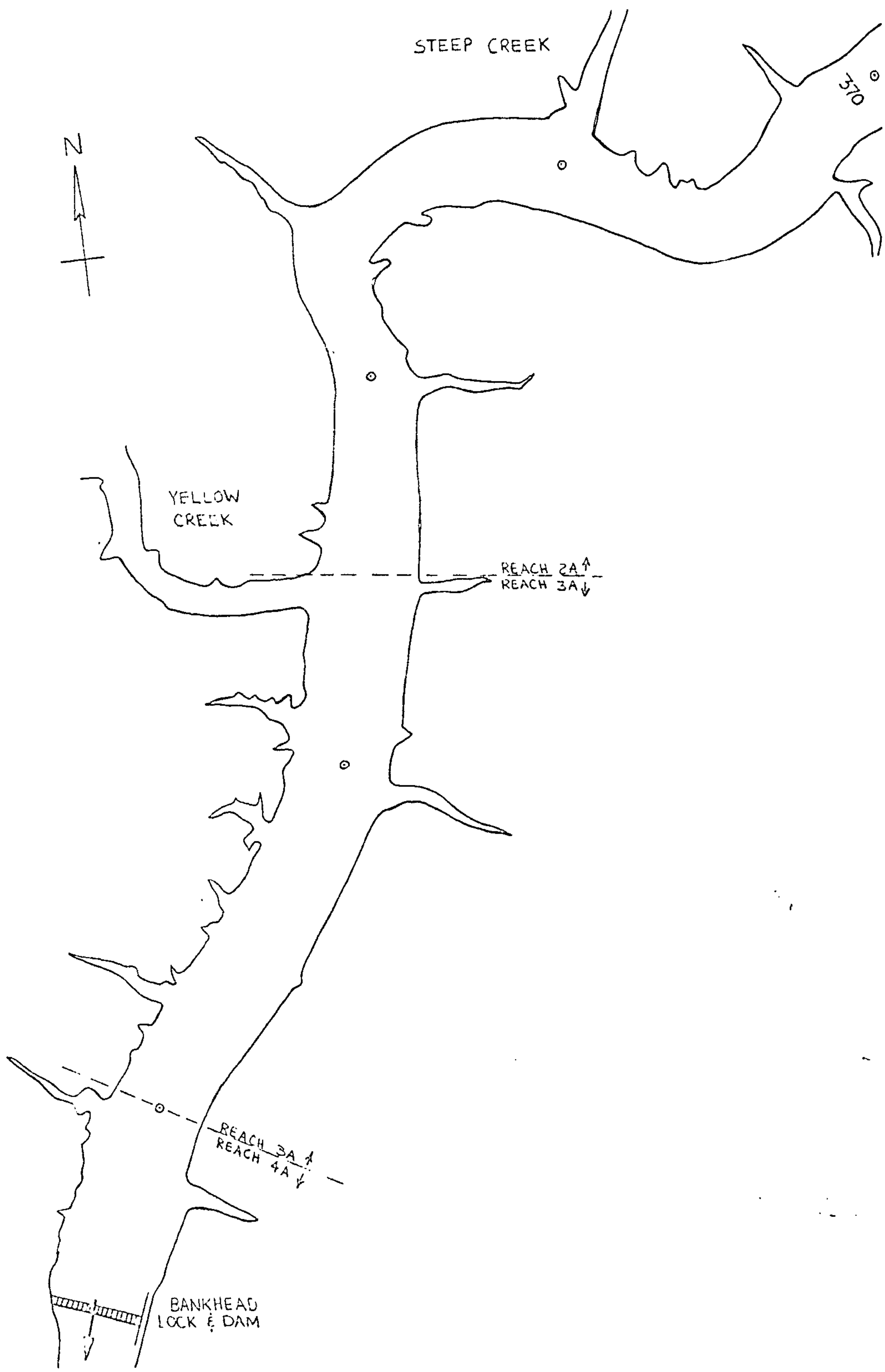
DETAILED MAPS OF THE SECTION OF
THE WARRIOR RIVER USED IN THE
MODELING STUDY

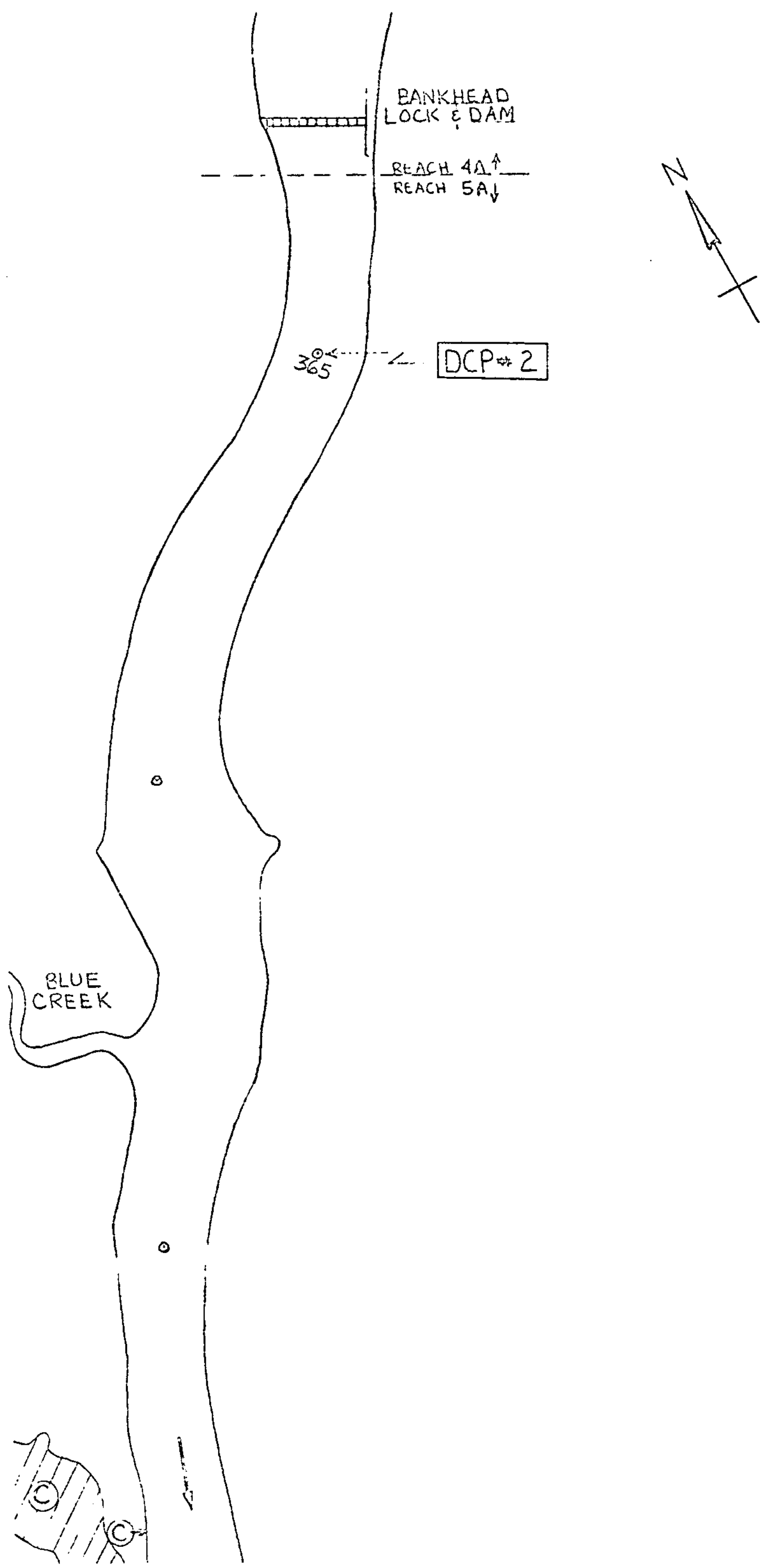

N
FORK
MULBERRY
PRESCOTT CREEK
DeBARDELEBEN COAL CORP.
WATERSIDE MINE
(ABANDONED)
E
BLACK WARRIOR RIVER
305
DCP #1
REACH 1A
LOCUST FORK
F
*NOT SHOWN ON MAP

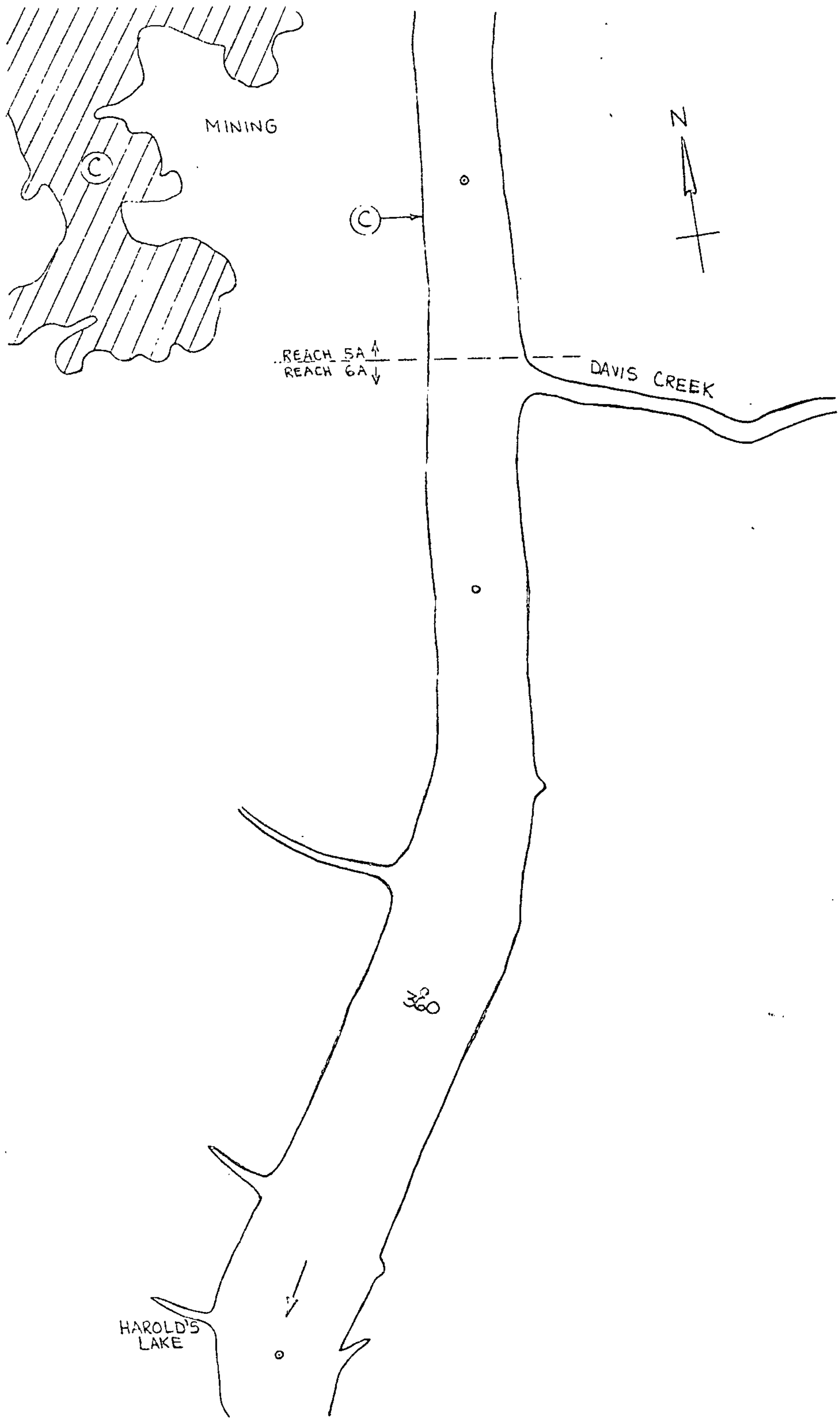

E
E
FRILEY'S CREEK
N
REACH 1A
REACH 2A
VALLEY CREEK
SHORT CREEK
FERRY
SHOAL CREEK
CREEK
380

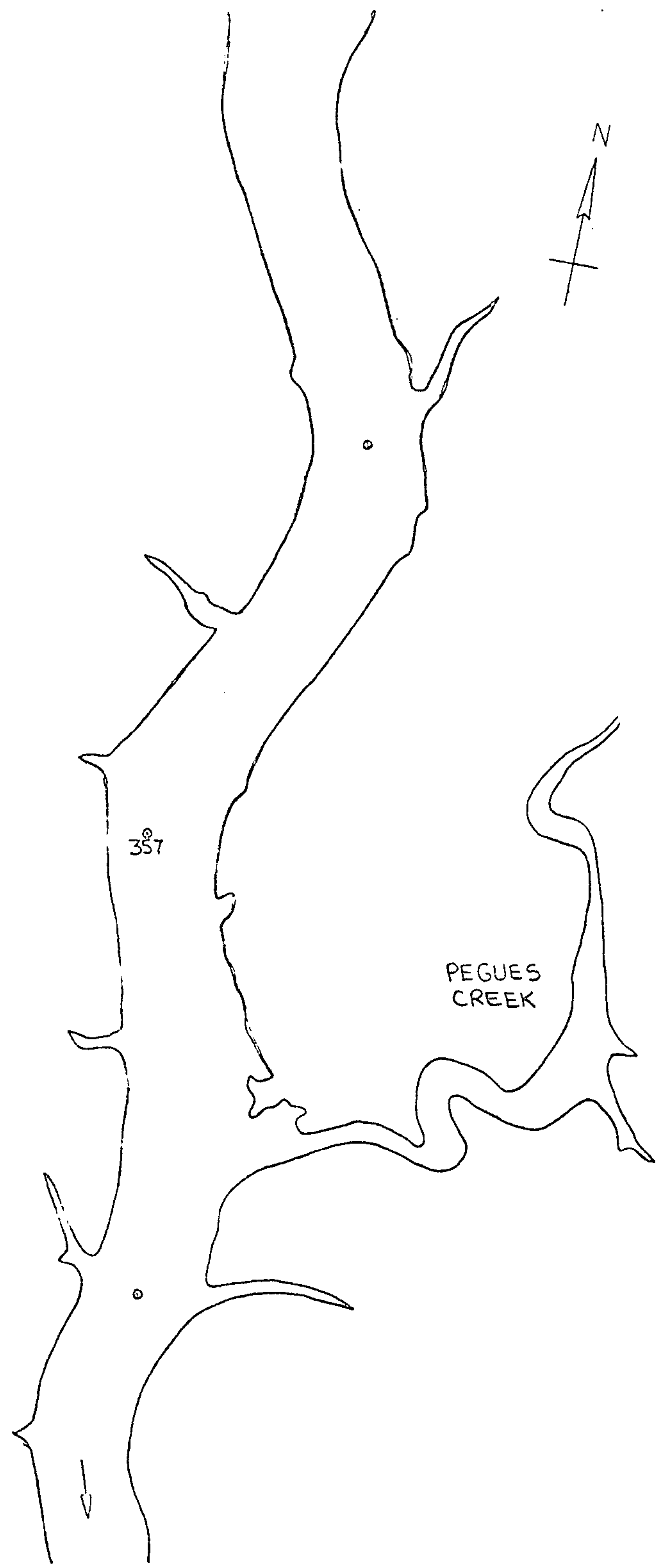


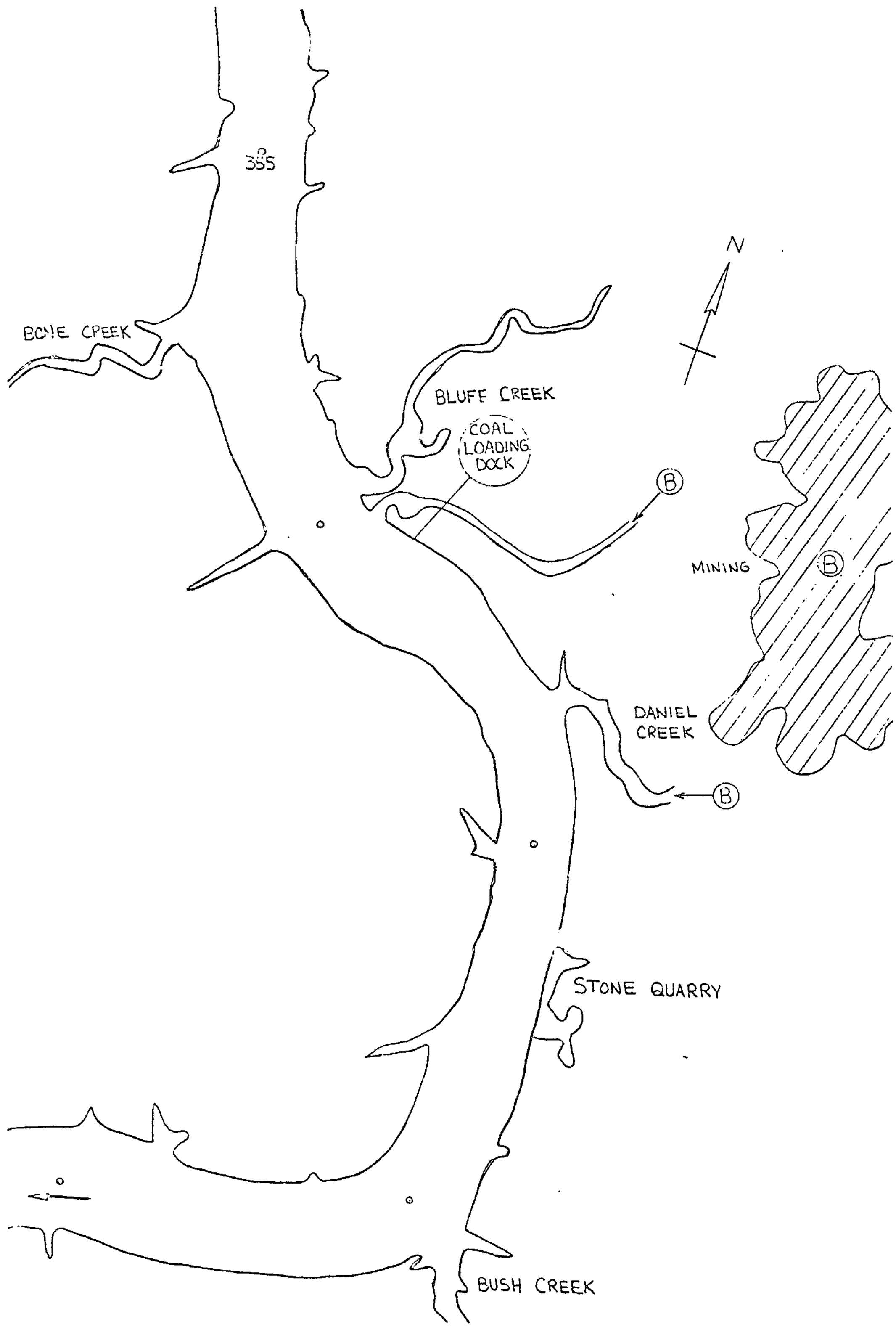
LITTLE SHOAL
CREEK
375
CAMP CREEK
BIG SHOAL
CREEK
D
N
* STRIPPING
AREA D NOT
SHOWN ON MAP
370
DOUBLE
BRANCH
WILLOW STUMP

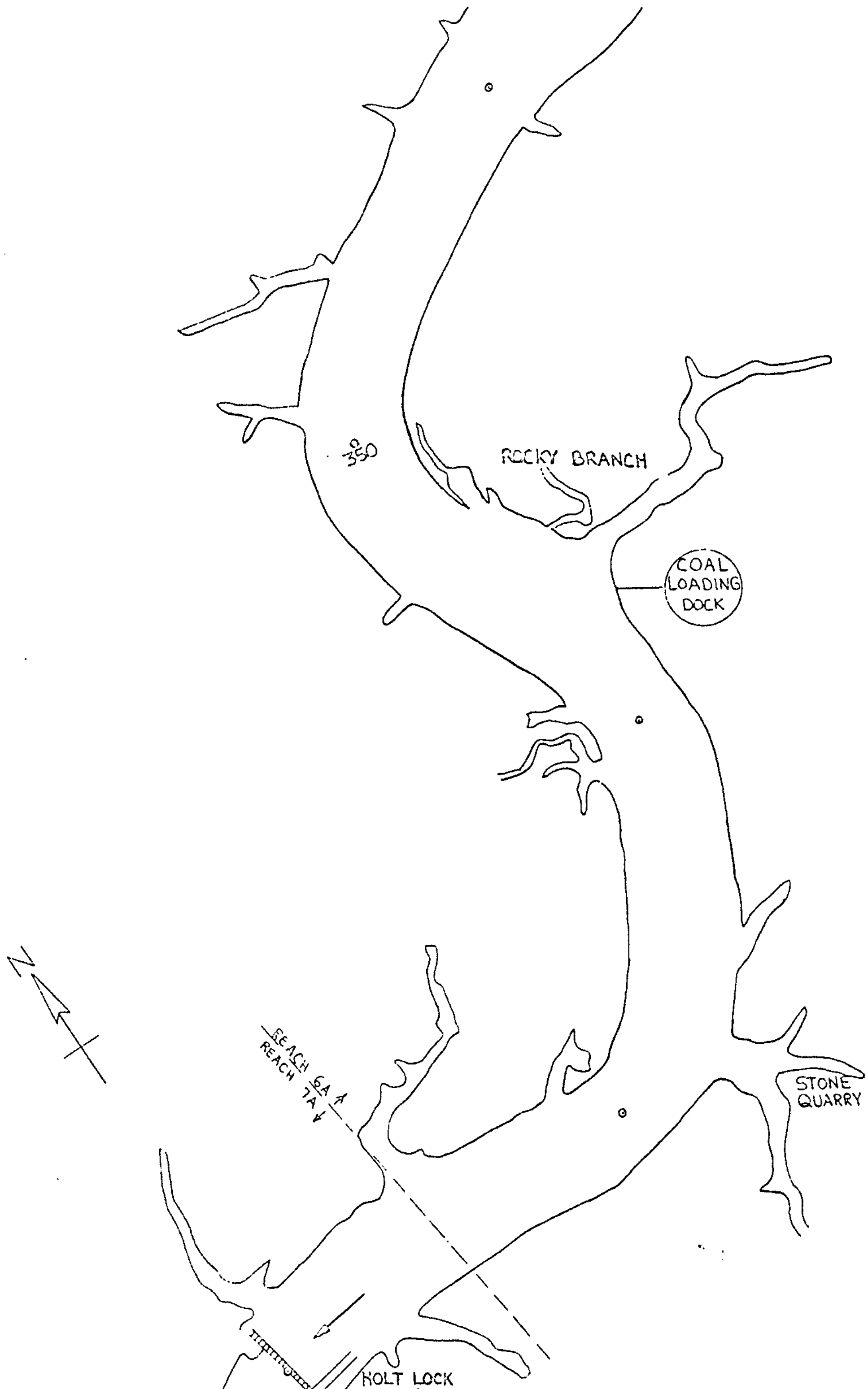

STEEP CREEK
370
N
YELLOW CREEK
REACH 2A
REACH 3A
REACH 3A
REACH 4A
BANKHEAD LOCK & DAM

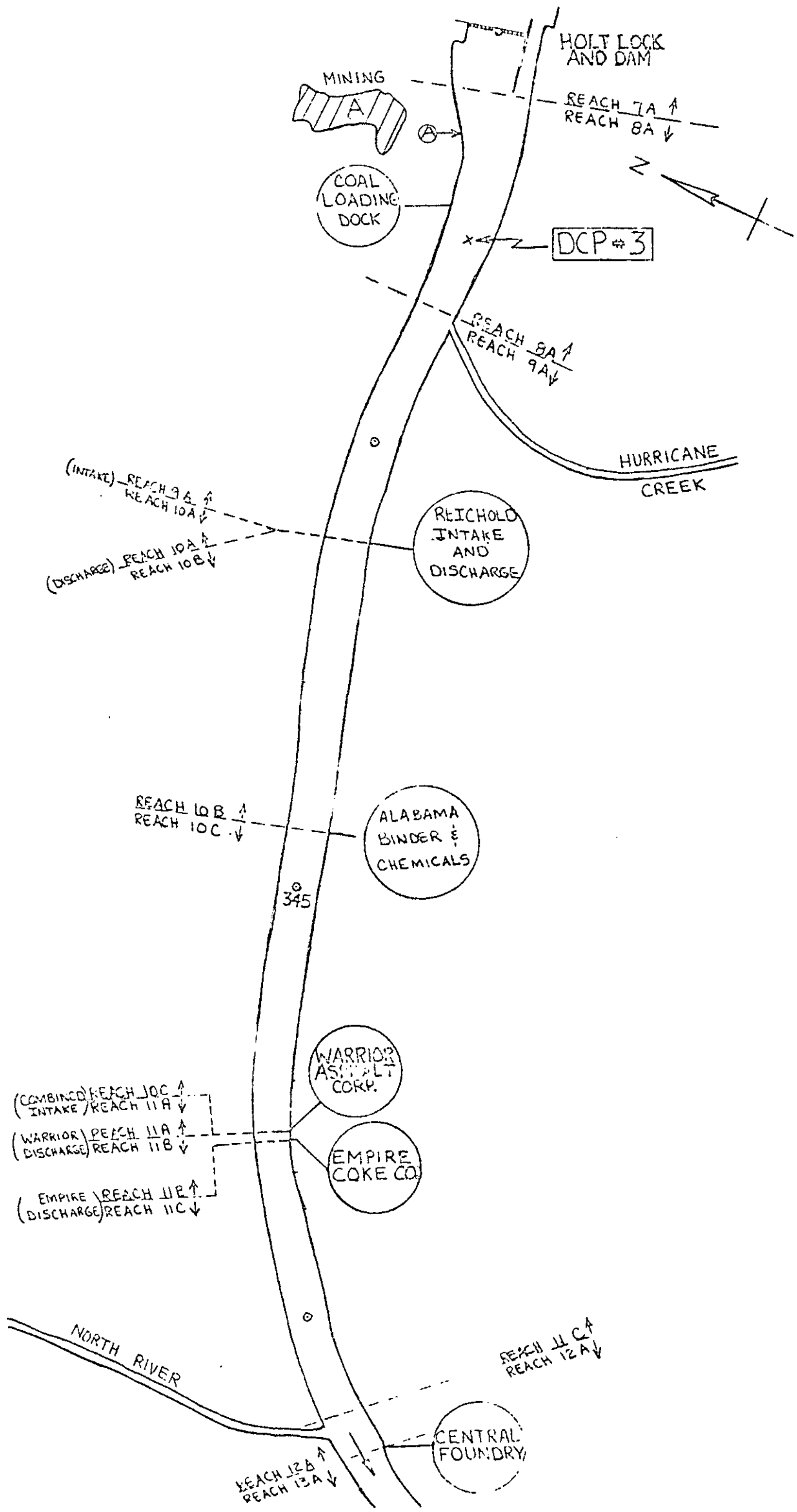

BANKHEAD
LOCK & DAM
REACH 4A
REACH 5A
N
365
DCP#2
BLUE
CREEK
C
C

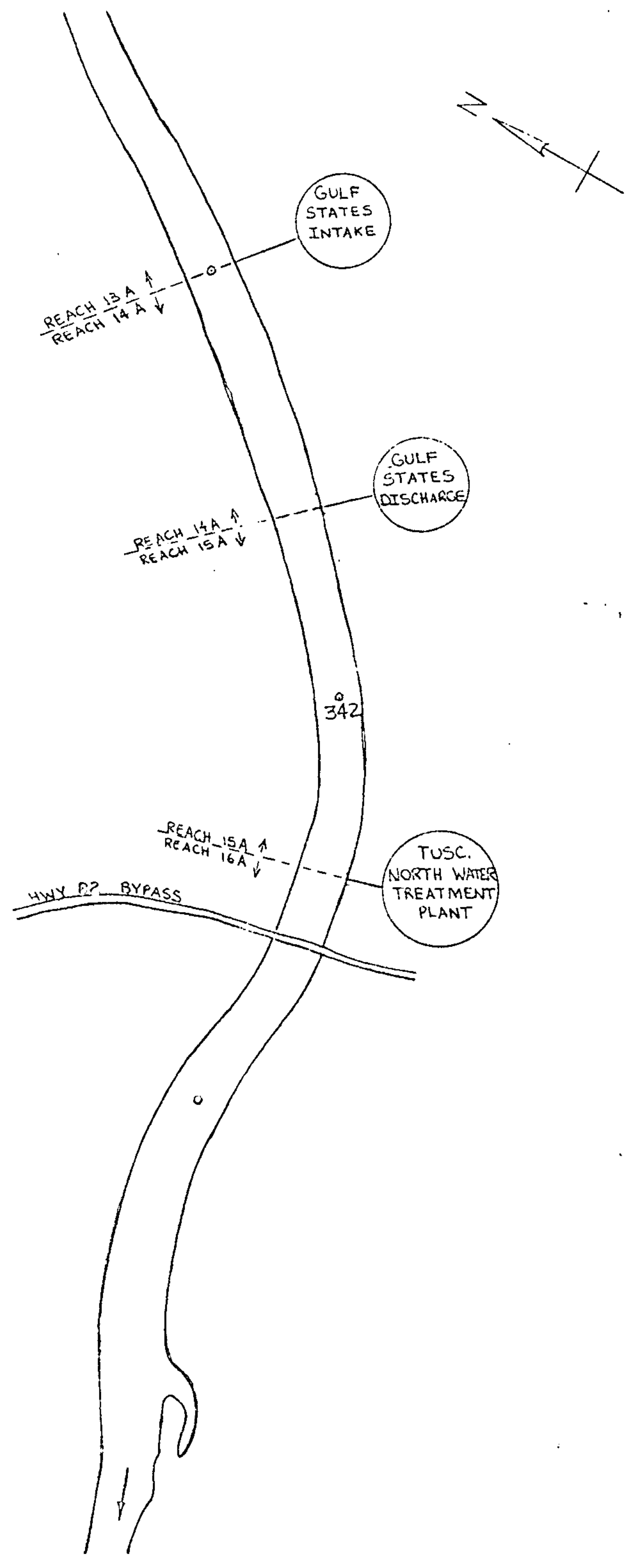

MINING
N
REACH 5A
REACH 6A
DAVIS CREEK
360
HAROLD'S
LAKE

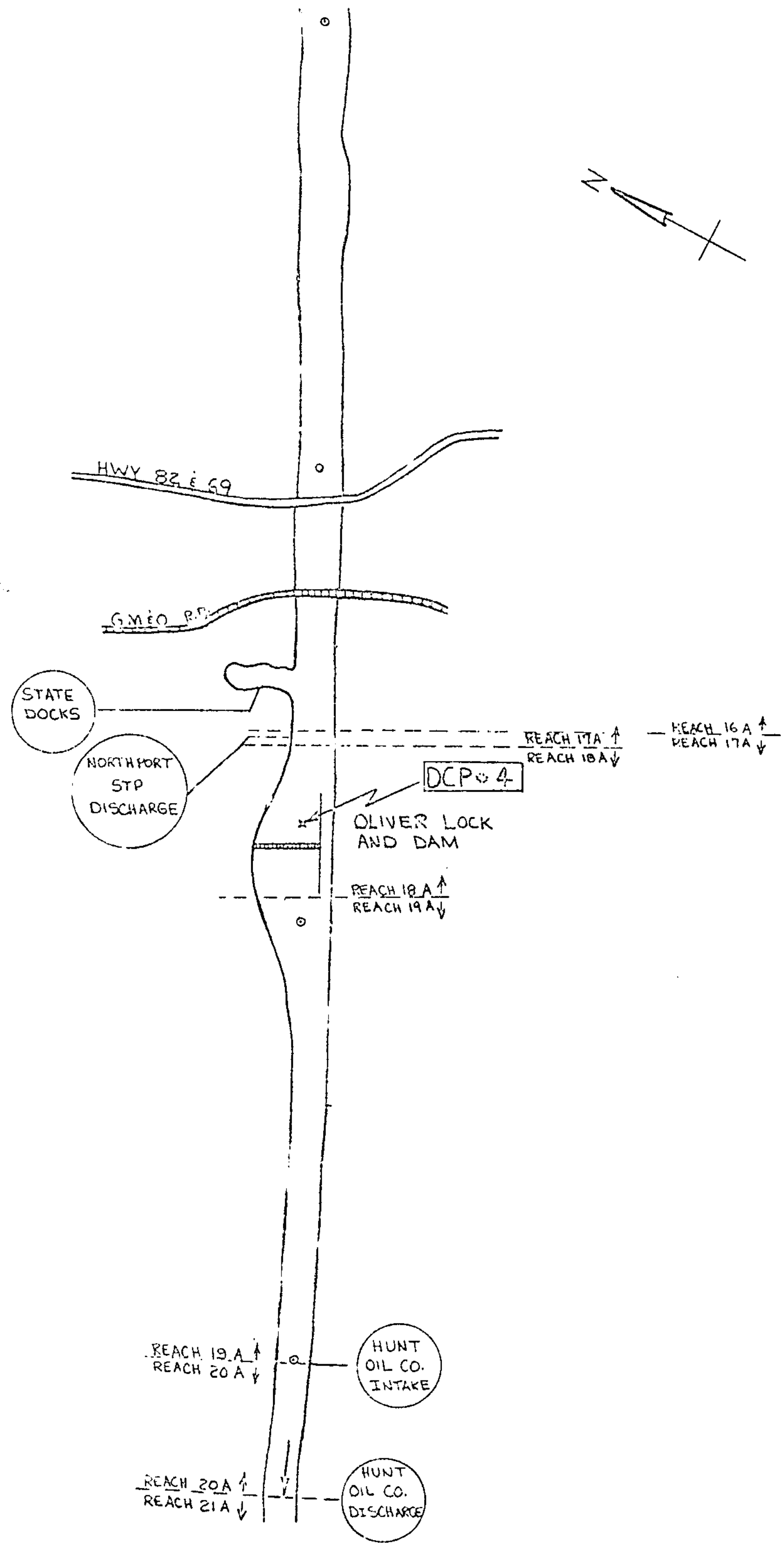

N
357
PEGUES
CREEK

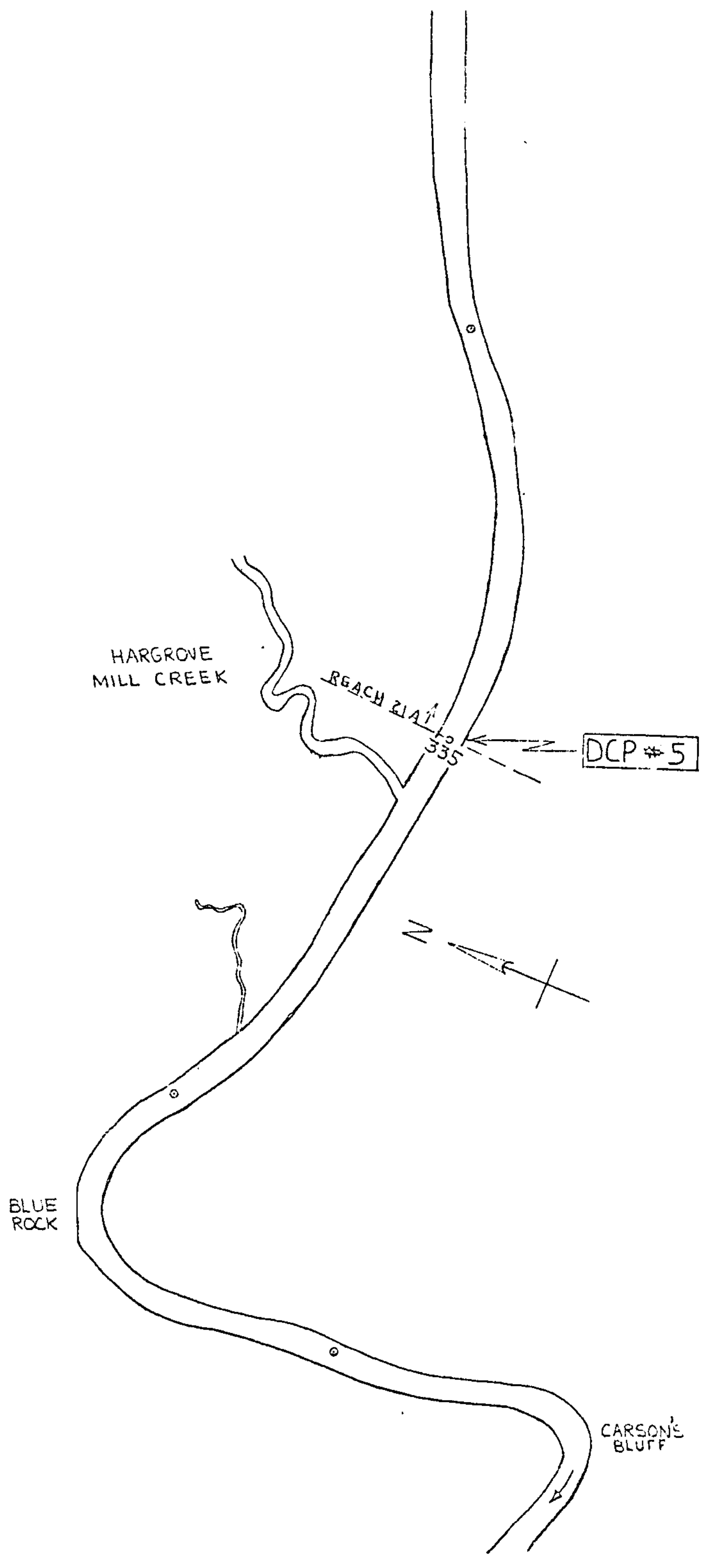

N
BONE CREEK
BLUFF CREEK
COAL
LOADING
DOCK
B
MINING
B
DANIEL
CREEK
B
STONE QUARRY
BUSH CREEK


350
ROCKY BRANCH
COAL LOADING DOCK
N
REACH 6A
REACH 7A
STONE QUARRY
HOLT LOCK AND DAM


HOLT LOCK AND DAM
MINING
A
REACH 7A
REACH 8A
N
COAL LOADING DOCK
DCP #3
REACH 8A
REACH 9A
HURRICANE CREEK
(INTAKE) REACH 9A
REACH 10A
(DISCHARGE) REACH 10A
REACH 10B
REICHOLD INTAKE AND DISCHARGE
REACH 10B
REACH 10C
ALABAMA BINDER & CHEMICALS
345
WARRIOR ASPHALT CORP.
(COMBINED INTAKE) REACH 10C
REACH 11A
(WARRIOR DISCHARGE) REACH 11A
REACH 11B
EMPIRE COKE CO.
(EMPIRE DISCHARGE) REACH 11B
REACH 11C
NORTH RIVER
REACH 11C
REACH 12A
CENTRAL FOUNDRY
REACH 12A
REACH 13A


N
GULF STATES INTAKE
REACH 13 A
REACH 14 A
GULF STATES DISCHARGE
REACH 14 A
REACH 15 A
342
REACH 15 A
REACH 16 A
TUSC. NORTH WATER TREATMENT PLANT
HWY
BYPASS


HWY 82 & 69
G.M.&O. R.R.
STATE DOCKS
NORTHPORT STP DISCHARGE
REACH 17A ↑
REACH 18A ↓
REACH 16 A ↑
REACH 17A ↓
DCP-4
OLIVER LOCK AND DAM
REACH 18 A ↑
REACH 19 A ↓
REACH 19 A ↑
REACH 20 A ↓
HUNT OIL CO. INTAKE
REACH 20 A ↑
REACH 21 A ↓
HUNT OIL CO. DISCHARGE


HARGROVE
MILL CREEK
REACH 21A1
335
DCP # 5
N
BLUE
ROCK
CARSON'S
BLUFF

BIBLIOGRAPHY

1. "ERTS." Pamphlet, National Aeronautics and Space Administration, Washington, D. C. (1972).

2. "A Joint Project to Study the Feasibility of Applying Remotely Sensed Data in the Management of Natural Resources and the Improvement of Environmental Quality in Alabama." Progress Report No. 1, Bureau of Engineering Research, The University of Alabama, Tuscaloosa (1972).

3. "Investigation Using Data in Alabama from Earth Resources Technology Satellite (ERTS A)." Technical Proposal Number 321, Bureau of Engineering Research, The University of Alabama, Tuscaloosa (1971).

4. Weaver, Leo, "Stream Surveillance Programs." Journal of the Water Pollution Control Federation, **38**, 1334 (1966).

5. Ballinger, Dwight G., "Effective Water Pollution Control Requires Accurate Data." Environmental Science and Technology, **1**, 612

6. Ballinger, Dwight G., "Automated Water Quality Monitoring." Environmental Science and Technology, **2**, 606 (1968).

7. Morton, Rex, Personal Communication. Marshall Space Flight Center, Huntsville, Alabama (1972).

8. "A Joint Project to Study the Feasibility of Applying Remotely Sensed Data in the Management of Natural Resources and the Improvement of Environmental Quality in Alabama." First Bimonthly Progress Report, Bureau of Engineering Research, The University of Alabama, Tuscaloosa (1972).

9. Streeter, H. W., and Phelps, E. B., "A Study of the Pollution and Natural Purification of the Ohio River." Bulletin No. 146, U. S. Public Health Service, Washington, D. C. (1925).

10. Goodman, Alvin S., "Use of Mathematical Models in Water Quality Control Studies." Water Pollution Control Research Series, Environmental Protection Agency, Washington, D. C. (1969).

11. "QUAL-I--Simulation of Water Quality in Streams and Canals." Texas Water Development Board, Austin (1970).

12. "DOSAG-I--Simulation of Water Quality in Streams and Canals." Texas Water Development Board, Austin (1970).

13. Pyatt, E. E., "A Model for Quantifying Flow Augmentation Benefits." Final Report to Southeast Region, Environmental Protection Agency, Atlanta, Georgia (1969).

14. Churchill, Milo A., and Nicholas, William R., "Effects of Impoundments on Water Quality." Journal of the Sanitary Engineering Division, ASCE, 93, SA6, 73 (1967).

15. McCormack, D. J., and Perlis, H. J., "The Development of an Optimum Multivariable Measurement Policy in a Distributed Parameter System." Second Southeastern Symposium on System Theory, Gainesville, Florida (1970).

16. Anderson, Melvin W., and Day, H. J., "Regional Management of Water Quality--A Systems Approach." Journal of the Water Pollution Control Federation, 40, 1679 (1968).

17. Klein, William L., Dunsmore, David A., and Horton, Robert K., "An Integrated Monitoring System for Water Quality Management in the Ohio Valley." Environmental Science and Technology, 2, 764 (1968).

18. Testerman, M. K., "Digital Systems for On-Site Collection for Water Quality Analysis." Publication No. 8, Water Resources Research Center, University of Arkansas, Fayetteville (1970).

19. Pence, George D., Jr., Geglic, John M., and Thomann, Robert V., "Time-Varying Dissolved Oxygen Model." Journal of the Sanitary Engineering Division, ASCE, 94, SA2, 381 (1968).

20. "Black Warrior-Tombigbee Rivers Navigation Charts." U. S. Army Corps of Engineers, Mobile, Alabama (1971).

21. Eckenfelder, W. W., Jr., and Krenkel, P. A., "Water Quality Engineering for Industry." AIChe Today Series (1971).

22. O'Connor, D. J., and Dobbins, W. E., "Mechanism of Reaeration in Natural Streams." Transactions, ASCE, 123 (1958).

23. "Solubility of Atmospheric Oxygen in Water." Journal of the Sanitary Engineering Division, ASCE, 86,(July 1960).

24. "Effect of Holt Powerhouse on Water Quality of Black Warrior River." Project No. 2203, Federal Power Commission (1973).

B

25. Fuller, Robert R., Personal communication. Gulf States Paper Corporation, Tuscaloosa, Alabama (1973).

26. "Water Quality Control Information System (STORET) Handbook." Office of Water Programs, Environmental Protection Agency, Washington, D. C. (1972).

27. Miller, E. T., and Walters, J. V., "Use of STORET in Water Quality Management." Report to Geological Survey of Alabama, University, Alabama (1972).

28. Davis, Jack, Personal communication. Empire Coke Co., Holt, Alabama (1973).

29. Allen, Ronald A., Jr., and Bodenheimer, Vernon B., "Decomposition Rates for Kraft Mill Waste." Southern Pulp and Paper Manufacturer, **30**, 2 (1967).

30. "A Compilation of Surface Water Quality in Alabama." Circular 36, Geological Survey of Alabama, University, Alabama (1966).

31. "Flow Characteristics of Alabama Streams." Circular 32, Geological Survey of Alabama, University, Alabama (1968).

32. Horn, Charles, Personal communication. Alabama Water Improvement Commission, Montgomery (1973).

33. Woods, W. K., Personal communication. Warrior Asphalt Co., Holt, Alabama (1973).

34. Witherspoon, J. H., Personal communication. Central Foundry Co., Holt, Alabama (1973).

35. Sandifer, Thomas, Personal communication. Northport Sewage Treatment Plant, Northport, Alabama (1973).

36. McClure, Nathaniel DeMass, "A Historical Development and Prediction of the Future Water Quality in the Black Warrior River in the Vicinity of Tuscaloosa, Alabama." M. S. Thesis, College of Engineering, The University of Alabama, Tuscaloosa (1967).

37. Bowers, Willard, Personal communication. Alabama Power Company, Birmingham (1973).

38. "Water Resources Data for Alabama." Alabama District, Water Resources Division, U. S. Geological Survey, University, Alabama (1971).

39. "7-Day Low Flows and Flow Duration of Alabama Streams." Bulletin 87, Part A, Geological Survey of Alabama, University, Alabama (1967).

40. Plant records--1972. Tuscaloosa Water Treatment Plant, Tuscaloosa, Alabama.

41. "Black Warrior and Tombigbee Rivers." U. S. Army Corps of Engineers, Mobile, Alabama (1962).

42. Pollack, S. V., and Sterling, T. D., A Guide to PL/1. Holt Rinehart and Winston, Inc., New York, N. Y. (1969).